DETERIORATION AND REHABILITATION OF CONCRETE STRUCTURES IN HOT AND ARID REGIONS

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Reinforced Cement Concrete(RCC) has been in use for over a hundred years and has gained popularity very fast owing to the low cost and ease in availablity of its component materials. Furthermore, as a construction material, it offers great flexibility with respect to shape and size and could match very closely with the imagination of the architects and builders. Deterioration of concrete before it has served its expected life is a global phenomenon and the situation is particularly severe in hot and arid regions of the world where high temperature, humidity and salinity exist. There are many RCC structures built at a very high cost, which have exhibited deterioration of concrete even before they have been put to proper use. Owing to this many of them had to be demolished prematurely. In harsh or aggressive environments, which generally exists in Gulf more particularly in Sultanate of Oman, durable concrete cannot be produced by merely focusing on conventional strength and safety considerations. Here the concrete-environment interaction controls to a large extent the performance of materials and hence the concept of designing for durability is essential. In recent years intensive research in concrete durability has contributed specific information regarding the main parameters that exist in connection with concrete deterioration. Deterioration can be composed of several different mechanisms and design of repair work has to be such that it includes the removal of one or all of the parameters that cause the deterioration. The need for repair of a concrete structure can be due to some or all of the following reasons:1. safety consideration; 2. functional failure; 3.aesthetic reasons. Causes of deterioration throwing light on some of the solutions incorporating design of various structural elements are elucidated. Some of the deterioration mechanisms and their consequences along with the description of materials which should be used as protection measures against harsh and humid environment are also focussed.

Keywords: Concrete, Deterioration, Durability, Oman, Repair.

INTRODUCTION

The hot and humid climatic condition in Oman as well as in the whole of middle east, in many respect is unique in the world, yet the designers continue to adopt practices prevailing in other countries. The performance of concrete materials under adverse conditions needs to be taken into account while designing concrete structures. The first step is to recognize the important parameters inherent to the environment, materials and mixtures, construction practices and other service conditions, then they should be integrated technologically adopting suitable policies. In view of this an urgent and pressing requirement for the review of the needs of this region is felt necessary for recommending suitable materials and appropriate constuction technology.

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The requirement of fresh concrete is the consistency of the mix, such that it can be compacted without excessive effort. In addition to this the mix should be cohesive enough for transport and placement without segregation. The primary requirement of a good concrete in its hardened state is a satisfactory compressive strength and an adequate durability. The selection of proper materials and mix proportions no doubt are important in achieving the goal of producing concrete that will meet the requirements of strength and durability in a structure; however, the goal may still remain elusive if adequate attention is not paid to the environment to which concrete is subjected at the early age and in the course of its life. This may lead to deterioration in concrete elements at an early stage warranting for maintenance and repair.

The maintenance which follows the inspection may involve minor or major repair work, once the extent and cause of the problem is established. Otherwise, the problem may recur so that repeated repair work becomes necessary. But what is the expected life of the structure? Is it enough to repair it so that it will serve for a few more years, and then be demolished to make room for a new structure? Or is there a specific life, say 30 years, in which case repairs have to be much more substantial, which sometimes may be so uneconomical that demolition and replacement is justified.

MAINTENANCE OF THE DAMAGED CONCRETE

Any concrete structure must be maintained and, when damaged, must be repaired so as to restore its function. The damage in concrete structures may arise as a result of numerous causes, both external action and environmental degradation. It is important to ascertain the causes and the extent of the problem, so that repair undertaken must be effective. However, irrespective of the causes of deterioration, the repair strategy may be classified as follows:

- Cosmetic or minor repairs without any consideration for structural stability
- Major repairs involving expensive structural elements which may require support at the time of repair often warranting an assessment of the stability of the element concerned or the structure as a whole before and/or after the repairs
- Dismantling and reconstruction which is generally weighed against major repairs with regard to economy and the expected life of the structure after repairs have been carried out

CAUSES OF THE DETERIORATION OF CONCRETE

Physical causes
The physical causes of concrete deterioration can be divided into two categories:

- Loss of mass from a concrete surface due to abrasion
- Cracking due to temperature and humidity gradients, pressure due to crystallization of salts and structural loading.

Abrasion is due to the wear that takes place on the surface of the structure when severe abrasion conditions exist. It is recommended that, in addition to the use of hard aggregates, the concrete mixture should be proportioned to develop at least 40Mpa compressive strength after 28-days. Structural cracks at an early age generally arise due to shrinkage and drying, depending on the factors like size of the member, characteristics of concrete materials, and their mix proportions. Thermal shrinkage is of greater importance in large concrete elements. Some of the induced elastic stress is relived due to the visco-elastic (creep) behavior of the material. In porous materials, crystallization of salts from their supersaturated solution can produce pressure that is large enough to cause cracking.

Chemical causes
The chemical causes for deterioration of concrete can be grouped as follows:

- Hydrolysis of the components present in cement paste
- Reaction between aggressive fluids and cement paste
- Reactions involving formation of expansive products, such as ettringite in sulphate attack, alkali- silica gel in alkali-aggregate attack, and iron hydroxide in the corrosion of reinforcing steel in concrete.

In a well- hydrated Portland cement, the solid phase which is composed of calcium compounds (such as calcium silicate hydrate and calcium hydroxide) exists in a state of equilibrium with a high-pH pore fluid. And that is why it is in a state of chemical equilibrium when it comes in contact with an acidic environment. When it comes into contact with water, it tends to dissolve and leach away calcium compounds, thus causing a great loss in strength. With regard to reactions, most common are those involving acidic solutions containing anions which form soluble calcium salts, such as mineral acids (HCI, H_2SO_4, HNO_3) and organic acids found in food products (acetic, lactic acids). Un-reinforced concrete structures, such as pavements, retaining walls and dams would expand and crack as a result of Sulphate attack or alkali- aggregate reaction when the resulting expansion exceeds 0.05%, which is the limit for tensile strain in concrete.

Sulphate attack
Degradation of concrete as a result of chemical reactions between hydrated Portland cement and Sulphate ions can manifest in expansion and cracking or a progressive loss of cohesiveness and strength. The most vulnerable being the Sulphate attack which is due to calcium hydroxide and the alumina-bearing phases, hence protection against this can be done by using dense, quality concrete with a low water – cement ratio.

Alkali – aggregate reaction
Expansion and cracking of un-reinforced concrete leading to loss of cohesiveness, strength, and elasticity can also result from chemical reaction between certain reactive aggregates and alkalis in the cement paste. Aggregates containing amorphous or poorly crystalline forms of silica are known to be most vulnerable, although all silicate and silica minerals including some siliceous dolomite and limestone are also known to suffer to some extent from the alkali – aggregate attack.

Corrosion of reinforcing steel
Deterioration of concrete due to corrosion of embedded steel manifests itself in the form of expansion, cracking, and loss of cover, steel–concrete bond and reduction of the cross-sectional area of reinforcement leading to the collapse of the structure. Corrosion of reinforcing steel occurs as a result of an electrochemical process in which a part of the metal acts as an anode, whereas another part acts as a cathode. The anode process begins only after the protective or the passive iron oxide film normally present at the surface of steel is either removed by an acidic environment

(e.g.carbonation of concrete) or is made permeable by the action of chloride ions. The cathode process cannot occur until sufficient supply of oxygen and water is available at the steel surface. Electrical resistivity of unsaturated or dry concrete is high; however it gets reduced in the presence of moisture and salts. The mechanism by which concrete expands and cracks as a result of corrosion of reinforcing steel is due to an increase in the volume of solids which happens when metallic iron transforms into iron hydroxide rust or due to the swelling of poorly crystalline iron hydroxide which increases the hydraulic pressure of the pore fluid. Expansion will occur when the strength and the elastic modulus of concrete is significantly reduced due to the exposure of hydration products of cement such as carbonate, sulphate, and chloride to acidic ions.

FACTORS AFFECTING DURABILITY OF CONCRETE

Several factors like temperature, rainfall, wind, relative humidity, pollutants present in atmosphere, freezing, thawing, soil and ground water chemicals affect the durability of concrete. Due to high temperature, concrete structures deteriorate more rapidly when exposed to hot environment. They bear a significant effect on the durability of concrete thus influencing the rate of corrosion, chloride diffusion etc. High rainfall is responsible for wetness of concrete used in exposed conditions. If the concrete is made of high alkali cement or/and reactive aggregates, moist conditions will produce alkali slica reaction which could be detrimental to concrete. Relative humidity, which is dependent on temperature and rainfall can cause rapid drying of the surface of concrete causing drying and shrinkage. It can also effect the rate of carbonation and influence the rate of corrosion. Also wind is important in rapid drying of concrete which causes shrinkage cracks. In industrial areas the pollutants present in the atmosphere can cause considerable damage to concrete. CO_2 present in atmosphere reacts with free lime in concrete and produces carbonation of concrete. Freezing and thawing affects durability of concrete, especially in concrete pavement. Chemicals such as sulphates in ground water and soil can cause damage to the concrete, which in turn affects the durability.

Further the following conditions have a direct effect on the final quality of the concrete:

- Hot weather or strong winds dry out concrete during transport; so open containers such as lorries, dumpers, skips and barrows should be covered by Tarpaulins
- Heavy rains make the mix too wet, so again open containers should be covered
- If a container leaks, mortar will be lost in transit, as a result workability is affected
- Concrete gets stiffened rapidly due to hot weather
- Contamination of the concrete by oil or dirt from equipment or by dust, affects the quality
- Segregation can occur through incorrect use of chutes, placers, pipelines, and through long hands on conveyors or in vehicles over rough ground. After the haul in which some segregation has occurred, the concrete can be tipped into an intermediate hopper for remixing

- The skin of mortar left in a container dries very quickly and so it should be hosed off whenever there is a break in concrete production as well as at the end of the day

Out of many conditions that affect the performance, concreting in hot weather is the most predominant one.

HOT – WEATHER CONCERTING

The rate of hardening of concrete is greatly accelerated when the concrete temperature is appreciably higher than the optimum temperature of 50 to 60^0F(10 to 15.5^0C). 90^0F (32^0C) is considered a reasonable upper limit for concreting operations. In addition to a reduction in setting time, higher temperatures reduce the amount of slump for a given mix. If additional water is added to obtain the desired slump, cement also should be added or else water-cement ratio will be increased with a considerable reduction in the strength. High temperature, especially when accompanied by winds and low humidity increases the shrinkage of concrete which leads to surface cracking in concrete. The temperature of the plastic concrete may be lowered by mixing water with aggregates before mixing. Heat gained during hydration may be reduced by using type IV(low heat) cement or by adding a retarder, air entrainment and water reducing agents. Workability agents may be used to increase the workability of the mix without changing water/cement ratio. It is also advisable to reduce the maximum time before discharge of ready-mixed concrete from the normal 1½ to 1 hour or less. The use of shades or covers will be helpful in controlling the temperature of concrete after placement. Moist curing should be started immediately after finishing and should continue for atleast 24hours.

Research Method

As the present research work aims at arriving at suitable construction practices in hot and arid regions, some of the case studies depicting deteriorartion are considered. The case studies are analysed resorting to some of the visual observations based on physical invetory in view of the localised standard specifications. In one of the problem solving cases, observations were taken utilising suitable building performance equipment. Outcome of the present research work is drawn considering many case studies in Oman but only three typical ones are presented due to obvious reasons. Careful inventory and some of the observations noted through experimentation has helped in suggesting some of the suitable remedial measures for undertaking repair of the structures under consideration.

Though photographs taken show the extent and causes of the damage of concrete structures on the sites they are not included as a part of the text and shall be displayed later.

CASE STUDIES FROM OMAN

Various codes of practice and guidelines followed are mostly based on British Standards BS:8110:Part 1: 1997, BS:5400:Part1:1990, BS:5400: Part 4:1990, BS:5628:Part1:1992 and CIRIA guide. However, Table 1 presents current local criteria for RCC structures that need to be followed in the Gulf.

Table 1: Current local criteria for RCC in the Gulf

Exposure Conditions	RANGE OF SPECIFICATION LIMITS			
	Min.Cement content (kg/m^3)	Max. W/C ratio	Additional requirements	Min. cover for reinforcement (mm)
a.	300 to 320	0.52 to 0.50	-	30
b.	320	0.50	-	40
c.	320 to 350	0.50 to 0.45	-	40 to 50
d.(i)	300 to 320	0.50	-	40 to 50
(ii)	320 to 400	0.50 to 0.42	Tanking/membrane	40 to 50
e.	370 to 400	0.45 to 0.42	-	75 to 100
f.	400	0.50	-	40

(By courtesy of Muscat Municipality, Oman)

With respect to the severity of climate, Oman is divided into four different zones:

Conditions of Exposure in Different Areas

Zone I : The areas in northern part of Oman and the interiors at least 5 km away
(Moderate) from the sea
Zone II : The areas in northern part of Oman close to the sea
(Severe)
Zone III : The areas in Dhofar region at least 5km away from the sea
(Very Severe) :
Zone IV : The areas in Dhofar region close to the sea
(Extreme) Coastal structures

Further, Table 2 presents the requirements for concrete works depending on the region and Table 3, the specifications recommended for concrete as per the zones as mentioned above.

TABLE 2: **REQUIREMENTS FOR CONCRETE WORKS BASED ON THE REGION**

Description	***Requirement***
1.Minimum concrete grade	**Northern Region: 40N/mm^2** **Dhofar Region: 45N/mm^2**
2. Cement type	OPC for RCC and SRC in PCC below ground and in concrete block work
3.Cement Content	
i) Minimum	400 kg./m^3 of concrete
ii) Maximum	450 kg./m^3 of concrete
4.Maximum water – cement ratio	**0.40**
5.Limits on chlorides & sulphates by weight of cement	
i) Chloride (CI)	0.3%
ii) Sulphate (SO_3)	4.0%
6.Minimum concrete cover	
i) Superstructure	40mm (45mm for Dhofar Region)
ii) Substructure	50mm
iii) Foundations	75mm
iv) Piles/pile cap	80 – 100mm
6. Protective coating	
i) Superstructure	Surface sealant/Protective coating
ii) Substructure/Foundation	Bituminous coating

(By courtesy of Muscat Municipality, Oman)

Table 3: Recommended specifications for concrete works

Exposure condition	Min.Concrete grade (N/mm^2)	Min.Cement content kg/m^3 of concrete	Max. free water/cement ratio
Zone I	35	325	0.50
Zone II	40	375	0.45
Zone III	45	400	0.42
Zone VI	50	425	0.40

(By courtesy of Muscat Municipality, Oman)

Prayer Hall

The prayer hall was built in early seventies, and by 1986 extensive cracks and spalling of concrete from the ceiling was observed in the area below toilet due to the following reasons:

- The reinforcement was badly corroded
- There was significant reduction in the diameter of reinforcement.
- There was dampness in the ceiling due to leakage of water from toilet on the upper floor.

The area was out of use, so it was necessary at that stage to restore the area for re–use, hence after careful inventory and location of problems concerning to various elements, repair to the concrete works was felt indispensable.

Repair strategy:

- To stop leakage of water from the upper floor, the toilet was completely dismantled. The sunk floor was treated for waterproofing. The damaged pipes were replaced and thoroughly checked for water tightness.
- Consideration for concrete repair: The contaminated concrete was removed from around the reinforcement, which also facilitated attending to the reinforcement. The surrounding concrete surface required sealing to stop any future contamination from reaching the reinforcement. This could be achieved by coating the surface with a bonding agent which normally serves dual purpose of sealing the concrete surface and also providing a bonding aid for the subsequent repair material. The reinforcement required cleaning and a protective coating to insulate it from the surrounding medium. As resinous repair material was stronger but susceptible to higher temperature, cement based repair material though weaker but unaffected by higher temperatures was tried.

Discussion: Reinforcement was exposed until at least 50mm and concrete from its behind was chiselled out for a depth of 20 – 25mm. Sand blast was carried out to the surface of steel/concrete to remove rust and any loose material. Protective coating to steel reinforcement also was underatken with application of bonding aid to steel and concrete. Repair material was applied and it was plastered smoothly to facilitate painting later. It was decided to weld additional bars where the loss of reinforcement was more than 10% based on the cushion available in the design of existing reinforcement.

A Residential Villa

A residential villa located on the south west cost of Oman about 100m in the vicinity of the sea was considered for the study. It was subjected to very severe climatic conditions like high humidity and salinity. It was more than 10 years old at the time of inspection.

On inventory survey it was observed that the soffit of roof slabs had deteriorated badly. In one large room the concrete cover had spelled away almost completely exposing the reinforcement. In slab of the first floor, rusting of reinforcement and spalling of concrete to a much greater extent when compared to other roof slabs was seen. The concrete appeared to be of very poor quality with low cement content. The cover to reinforcement at some places was as low as 8–10mm. There was a possibility that chloride present in pounding water might have contaminated coarse and fine aggregates used in the concrete. This and the unsatisfactory condition of roof finishes could have resulted in seepage of water into the roof slab carrying with it the salt which was deposited on roof by wind blown salt laden mist from the sea. Thus the concrete in the roof slab was subjected to contamination from external sources which had resulted in severe corrosion.

Discussion: From the quality of material and workmanship it was quite evident that consideration for special requirements of the environment with respect to quality of concrete, clear cover, etc. was inadequate. It appeared that the supervision lacked in quality. Another important point brought to light was the absence of water proofing treatment to the roof, which does not normally come under the purview of the structural design engineer. Similarly, all balconies and terraces exposed to rain should be properly waterproofed, laid to slop with drainage outlets for proper drainage of water.

The Sea Wall

The seawall 571m (approx.) long was built in 1974. It consisted of anchored steel sheet piling with a lightly reinforced capping beam. It was subjected to wave action and seawater spray during certain times of the year (July to September). Within the next few years of construction, rusting of reinforcement and spalling of concrete was observed.

The following experiments were conducted using building performance equipment to assess the present condition of the wall:

Cover Meter Survey: The specified concrete cover was 50mm. At many places where the reinforcement has been uncovered in areas of spalling the cover was found to be less than 50mm; and in some cases less than 15mm.

Chloride Profile: The high values of this were observed near the surface and it was drastically reduced at a distance of 60–80mm from the surface. Further, high concentration of chloride has been observed in areas of seawall which are subjected to the spray of sea water.

Sulphate Profile: It appears to be fairly uniform through out the depth with values varying from 0.35 to 0.50% when expressed as percentage of SO_3 by weight of concrete. The values are less than the acceptable limit of 4% by weight of cement.

Half – Cell Potential Survey: Results of half – cell potential survey indicated that apart from visible areas of spalling and cracking, the reinforcement appeared to be in a passive (non–corroding) state at the time of investigation. The half – cell potential in most of the unaffected areas measured above (-) 200 UV. It was between (-) 200 to (-) 350 UV in affected areas and below (-) 350 UV in areas of serious damage.

Resistivity: Resistivity measurements in all cases gave results in excess of 10,000 ohm/cm.

Observation: The corrosion of reinforcement had direct relationship with the cover to reinforcement. Even at positions were the design cover of 50mm was achieved, chloride profiles and exposure of reinforcement indicated that corrosion had already been started or might start soon. The high resistivity of the concrete might slow down the spread of corrosion but most likely the deterioration of the wall would continue gradually.

Repair Strategy: The consultants suggested methods for repair along with a suitable protective coating to be applied on the surface to prevent further ingress of oxygen, moisture and salt. However, major repairs were not carried out at that stage and no protective coating was applied, carrying out patch repairs to spalled areas. While the permanent solution to the problem of concrete deterioration of the capping beam was still under consideration, the steel sheet piles also started exhibiting corrosion severely at many places. However, discussions held led to adoption of fiber reinforced concrete in the place of reinforced concrete.

Discussion: The specified concrete cover of 50mm was low for a seawall in this region in view of the local extreme climatic conditions of high temperature, humidity and salinity. More so all these factors contribute severely for rapid corrosion of reinforcement.

OUTCOME

Based on the research work undertaken and after careful evaluation of many concrete structures in Oman, the following recommendations are made:

- It had been seen that the chloride ingress was significant (crossing the limit) upto a depth of 60mm from the surface, which dropped rapidly upto 80mm and beyond in many concrete structures. From this observation it may be concluded that the clear cover to reinforcement is not uniform throughout the concrete structures.
- It has been found from experience that the maximum chloride content which is unlikely to cause corrosion at a serious rate in uncarbonated concrete is about 0.5% CI by weight of cement. Wherever there is a possibility of concrete being exposed to windburn salts, sea water, sea spray, or to soil or groundwater contaminated chloride, the chloride content of the original mix should be kept to a minimum.
- The Sulphate in concrete (from whatever source) which reacts with aluminates in cement to from Sulpho – aluminates; which causes disintegration of concrete, must be addressed properly. SRC, which may be used in concrete to guard against Sulphate attack, contains lower percentage of aluminates (<4% C_3A). As aluminates otherwise bind in this with chloride ions and help against chloride induced corrosion, it is not recommended for RCC.
- Cement content of the mix should be enough to give the required durability, but it may need to be increased to more than this amount to give the required workability within the appropriate w/c ratio. When it is lowered for better

strength and more compactness (less permeability) it may be required to use plasticizers for better workability in view of the upper limit to the amount of cement that can be used.

- Another important point brought to light is the importance of water proofing treatment to the roofs which does not normally come under the purview of the structural design engineers. Similarly, all balconies and terraces exposed to rain should be properly waterproofed, laid to slop with drainage outlets for proper drainage of water.
- Protective coatings like surface water repellents, un-reinforced electrometric coatings, glass fibers, epoxy, and polyester resin can be used to safeguard concrete surfaces which are in contact with water.
- Epoxy coated and Stainless steel reinforcing bars can be employed based on the need and purpose. Cathodic protection technique can also be experimented as a repair mechanism though it is a costly affair.
- Quality assurance and quality control: Repair of a concrete structure is difficult and time consuming. Therefore, it is essential that whenever durability problems arise either out of incompatibility of material or due to environmental factors, both the design engineers and construction engineer should take all possible measures to combat the anticipated durability problem. An organization that follows an established quality assurance system will be able to provide a durable structure.

For an existing building there are ways to predict deterioration and the time of commencement of corrosion of reinforcement and also the severity of it, based on carbonation, chloride profile and other field tests. It may also be possible to predict the onset of corrosion in a new building based on general observation and statistical data on existing buildings in the surrounding areas.

SCOPE FOR FUTURE WORK

Oman, having extreme calamities of temperature and heat requires good construction practices featuring concrete and RCC. Hence, in future, along with good construction practices quality control and cement resisting high temperature and heat has to be employed in construction. Micro silica concrete or ferro-cement technique may be employed in the field to address the problems of concrete deterioration and for remedial measures of concrete.

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