EXPERIENCES WITH REHABILITATION OPTIONS FOR CONCRETE STRUCTURES IN MADINAT AL-JUBAIL AL-SINAIYAH

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ABSTRACT

Concrete structures in the Arabian Gulf region are exposed to one of the most severe conditions in the world. High salinity, particularly high concentrations of chloride and sulfate salts in groundwater and soil, initiates and accelerates concrete corrosion. Also, high temperature during summer aggravates the corrosion problems by increasing the corrosion rate.

This paper presents a discussion on the following:

- Influence of environmental factors on reinforcement corrosion and other common concrete deterioration that are normally encountered in the Arabian Gulf region.
- Interactions between the service environment and the chemical and physical concrete properties.
- Overall concrete durability problems.
- Common concrete repair options.
- Several case histories of concrete repair options used in Madinat Al-Jubail Al-Sinaiyah (Al-Jubail Industrial City).

KEYWORDS

Environment, concrete, reinforcement, corrosion, cathodic protection, coatings.

INTRODUCTION

The last two decades have seen the transformation of the Arabian Gulf Countries into the most intense area of major construction in the world. However, within a short time an increasing number of feedback reports from the field on the low durability of concrete construction in the Gulf States has made it exigent to focus attention on the deterioration mechanisms and preventive measures.

An examination of the low durability of concrete construction in the region should begin with the local geomorphic and climatic environmental conditions which are characterized by marginal aggregates, high temperature-humidity regimes and severe ground and ambient salinity. The coarse aggregates available in the area are almost entirely limestone and dolomites of the younger tertiary age. These types are known to yield marginal aggregate material that is porous, absorptive, relatively soft and dusty. Aeolian dune and beach sands form the main sources of fine aggregate. These sands are usually absorptive, fine, poorly graded, and above all they are heavily contaminated with chloride and sulfate salts.

The main causal factors of concrete deterioration in the region, in decreasing order of importance are (a) corrosion of reinforcement, (b) salt attack and cracking due to shrinkage (c) thermal gradients, and (d) aggregate-cement reactivity (ref. 1). Spalling of concrete due to rebar corrosion and degradation due to salt attack, however, outweigh all other forms of deterioration. Both of these factors are the visible manifestations of excessive salt either included in the concrete through the aggregates, mix water and/or subsequent ingress through cracks and pores in concrete. Contamination of concrete by salts could easily occur in unprotected concrete structures as calcium, magnesium and the sodium salts of sulfates, chlorides and carbonates are found in profused quantities in the ground, groundwater and the moisture-laden environment of the Gulf.

The aggressive service conditions and resulting concrete deterioration discussed above necessitate the production of quality concrete in the region, which is dense and highly impervious. The concrete should be sufficiently dense to inhibit the penetration of chloride and sulfate salts into concrete pores which are uniquely effective in setting up corrosion of rebars and the deterioration of concrete.

Concrete mixes must also be designed to evolve as heat of hydration as possible at early ages, and be, as much as possible, free from plastic and drying shrinkage cracking.

In addition to producing and placing good quality concrete, some exposures require supplemental protective measures in order to achieve the desired concrete durability.

CONCRETE EFFECTS

Any variations in the concrete that reduce its permeability to water, chlorides and oxygen will work toward prevention of reinforcement corrosion. This illustrates the effect of high permeability concrete against diffusion of detrimental ions into concrete pores. Also, the type of Portland cement used can have a significant effect on concrete durability. Aluminates in the cement react with chloride ion forming insoluble tricalcium chloroaluminate and thereby improving the resistance to reinforcement corrosion. Type I cement, containing approximately 12% tricalcium aluminate (C_3A) is three to five times more effective in removing chloride ions than Type V which contains about 4% C_3A (ref. 2).

The use of pozzolans tend to reduce the susceptibility to reinforcement corrosion because their use reduces permeability. This effect outweighs any reduction in pH that might result from the reaction between the pozzolans and the free lime in the concrete. Water-reducing admixtures, by virtue of their effect on permeability, may also be expected to reduce susceptibility to reinforcement corrosion.

Salt contaminants in the concrete ingredients should also be controlled so that the amount of detrimental salts is kept within certain tolerable limits.

DETERIORATION MECHANISMS

Reinforcing Steel Corrosion. The corrosion of steel in concrete is generally considered to be an electrochemical process. The pore fluids within concrete have normally pH of over 13. At pH levels above 11.5, a tightly adhering coating of gamma ferric oxide forms on steel surfaces, which normally prevents corrosion. However, the presence of chloride ions in certain concentrations within the concrete at the level of the reinforcement initiates corrosion of the reinforcement. There are also indications that the bisulfate ions may initiate corrosion of reinforcement in concrete.

Metal loss and the build-up of corrosion products occur at the anodic areas of corrosion cells. The resulting corrosion products occupy about 2 to 8 times the volume of the original steel from which they were formed, resulting in stresses that crack the concrete and eventually cause the concrete cover between the reinforcement and the nearest free surface to spall. The chemical reactions that occur at the anode corroding areas are believed to be as follows:

$$Fe^{o} + 2Cl^{-} \longrightarrow FeCl_2 + 2e^{-}$$
$$FeCl_2 + 2H_2O \longrightarrow Fe(OH)_2 + 2H^{+} + 2Cl^{-}$$

To be noticed is that (a) it is not necessary that oxygen be present at the anode for the corrosion process to proceed and (b) once the threshold chloride ion concentration is reached and corrosion commences, it is not necessary that additional chloride ions be supplied to sustain corrosion. Also, depending on availability of oxygen, other forms of corrosion reactions may take place.

The cathodic reactions consist of the electrolysis of water due to the emergence of electrons that are generated at the anode and travel through the steel to the cathodic areas as follows

$$1/2\ O_2 + H_2O + 2e^{-} \longrightarrow 2\ OH^{-}$$

In order for the cathodic reactions to proceed, sufficient oxygen must be present. Otherwise, polarization occurs at the cathodic areas due to the formation of an electrically insulating layer of hydrogen and the corrosion current is stopped. It is generally held that oxygen diffusion through concrete to depolarize the cathodic areas is the rate-controlling process in the corrosion of reinforcing steel in concrete.

Other elements needed to complete the galvanic cell circuitry are an electrolyte and an electronic path between the anodic and cathodic areas. Concrete and reinforcing steel generally meet this criterion.

In addition to the prerequisites for initiation and maintenance of corrosion of steel in concrete discussed above, differences in electrochemical potentials must exist at the surface of the reinforcement. However, there should not be any difficulty in satisfying this criterion since the electropotential differences can be created by differential concentrations of ions, breaks in mill scale, differential aeration, or other abnormality at the steel surfaces.

Sulphate Attack. It is widely accepted that that soluble sulfates attack concrete by reacting chemically with the free lime to produce calcium sulfate and with aluminate hydrates to produce calcium sulfoaluminate. Both of these are expansive reactions, but the latter is of far greater consequence, particularly if the form of the reaction product is ettringite (6CaO. Al_2O_3. $3CaSO_4$ $32H_2O$) as opposed to the monosulfate (4CaO. Al_2O_3. CaSO4. $12H_2O$). The result of these expansive reactions is severe cracking and disintegration of the concrete matrix.

Mechanical Damage by Salt Weathering. The Arabian Gulf region is among relatively few areas where the conditions leading to salt weathering exist. The environmental conditions such as very high evaporation rates, low precipitation, high temperatures, wide temperature variations, and soil, groundwater, and atmosphere that are excessively contaminated with soluble salts are responsible for this type of concrete deterioration. The mechanisms of the transfer of water through the concrete involve capillary and evaporation. The salts are precipitated in the concrete pores, and eventually stresses are produced by the accumulation and growth of salt deposits within the concrete cause disintegration of the concrete matrix.

Drying and Thermal Cracking. The drying conditions and temperature extremes of the Arabian Gulf region result in problems with cracking of concrete. Although this cracking is not usually of structural significance, the cracks provide the means for ingress by aggressive chemical species involved in concrete deterioration. The leaner concrete mixes tend to exhibit less drying shrinkage. The extent to which concrete is cured before being subjected to the environment also affects drying shrinkage. Also, thermal stresses should be taken into account in the structural design phase.

OPTIONS FOR REPAIRS AND PROTECTION

General. The options available for control of corrosion of steel in concrete depend upon whether they are being considered at the design stage, or whether they are being considered because of an identified problem, or because active corrosion is evident. The range of options for action is limited in number, and most fall into one of the following categories (ref. 3):

- Do nothing

- Effect conventional repairs on and as-needed basis
- Larger scale replacement or reconstruction
- Apply coatings or sealants
- Change the exposure environment
- Apply cathodic protection

Do Nothing . This course is not an option to control corrosion, but is frequently the c inadvertently adopted by those responsible for the maintenance of structures. Co structures are all too frequently assumed to have long life, low maintenance structur that little or no inspection or maintenance is provided. Once conditions are established allow corrosion to proceed, the appearance and integrity of a structure can be jeopardized very rapidly. To do nothing inevitably leads to progressive deterioration until some limit state is reached when action must be taken. This limit state may be appearance, danger to life, or inability to perform the design function. The cost of repairs at this stage is invariably higher than if the problem had been treated earlier, and economic repair may or may not be possible.

It is accepted that there are situations where the "do nothing" policy is the correct engineering or economic decision, but in the majority of cases this is often difficult to achieve in the Arabian Gulf region even with a proper inspection and maintenance program.

Conventional Repairs. In the local marine environment, the most frequently encountered cause of deterioration is a super-critical concentration of chlorides at the location of the reinforcement. It is of prime importance, if a conventional repair is being considered, to establish that all chloride contaminated concrete is cut out near the reinforcement. Allowing any contaminated material to remain will almost certainly cause the repairs to fail within a relatively short time.

Equally, unless the replacement material is resistant to the ingress of chloride, or additional measures are taken to prevent recontamination, then the file of the repair is unlikely to be longer than the time at which the original structure needed repair.

The "conventional" way to repair corrosion damaged concrete is to cut out the cover concrete up to about 20 cm behind the reinforcement, clean and coat the reinforcement, apply binding agent to stop chloride transfer from background concrete, and replace the material cut out.

Replacement or Reconstruction. This is essentially an extension of conventional repairs to a larger scale where more than just the outer layer of concrete is removed and replaced. Such a course of action is likely to involve more major temporary works, and/or the need to take a structure out of service while it is repaired.

This solution is likely to be adopted where deterioration has progressed to a point where conventional repairs would be ineffective or not cost effective. Reconstruction is more likely to be the preferred solution when damage is localized, and complete replacement of the affected area would restore the complete structure to an acceptable condition.

Coatings or Sealants. Surface treatments rarely provide means of control for corrosion unless they are applied either when the concrete is in good condition and uncontaminated, or immediately after a repair has been completed.

The range of products available is enormous. Coatings or sealants are made to resist the passage of water in the liquid phase but allow water vapor to pass; there are those which resist the passage of carbon dioxide, others specifically resistant to chloride ions, etc.

When considering a surface treatment it is important to note that :

- There is usually ample water and oxygen in concrete to allow corrosion to proceed.
- Few, if any coatings in practice, provide a completely impermeable barrier to a particular species.

This does not mean that surface treatments should never be applied. There are many marine structures where surface treatments have been used, and they appear to have been most beneficial.

The other category of coatings applicable to reinforced concrete is those applied to the reinforcement before concreting. Galvanized bar has been used with varying degrees of success, but in many cases it only delays the inevitable onset of corrosion under aggressive conditions.

Epoxy coated reinforcement is being used increasingly frequently in conditions where it is known that the structure will be subjected to severe exposure conditions and therefore consequent high risk of corrosion induced deterioration. The life expectancy of epoxy coated bar has yet to be proved in practice.

Change the Environment. Corrosion can sometimes be arrested by changing the conditions to which the structure is exposed. This technique is more usually applicable in process engineering, but can, and has found applications in civil engineering marine structures.

In open channel structures conveying seawater, the mode of operation could be changed to increase water level in channels. This will result in a reduction in the area of concrete suffering repeated saturation and evaporative drying and consequential concentration of chlorides. Also, immersed concrete areas tend to suffer less from effects of rebar corrosion probably due to stifling of oxygen in water covered areas.

Cathodic Protection. Cathodic protection (CP) is a commonly used technique for controlling corrosion particularly on buried or submerged steel structures. CP works by providing electrical energy in such a way as to promote the cathodic reaction (typically oxygen reduction) on the structure at the expense of the anodic (corroding) reaction.

The main problems for provision of CP is ensuring that the applied energy is distributed evenly across the structure and that sufficient energy is applied to mitigate corrosion across the entire surface of the reinforcing steel which requires protection.

For buried or fully submerged concrete structures, traditional CP systems and design methods can readily be employed. The options available include sacrificial anode or impressed current systems. Which type is most suitable depends upon local conditions, presence of coatings, and other factors.

In order to apply uniform CP current to the reinforcing steel in structures, which are neither buried nor submerged, a spatially distributed anode is required. A number of different generic types of anodes suitable for application to horizontal, vertical or soffit surfaces have been developed as follows:

- Conductive coatings
- Sprayed metallic coatings
- Conductive polymeric wire in cementitious overlay
- Expanded metal oxide coated titanium mesh with a cementitous overlay
- Discrete anode systems

Each of the different anodes has advantages and disadvantages particularly for the regards to suitability for marine applications.

CASE HISTORIES

Several case histories are presented below on experiences with concrete rehabilitation of important structures in Madinat Al-Jubail Al-Siniyah.

Concrete Seawater Cooling System. The main part of the system consists of an open canal system for distribution of seawater to industries for use as cooling water. The length of the canals is in excess of 10 km, and these are, in general, divided into three compartments by two reinforced concrete dividing walls.

After several years in use, corrosion became evident at the general water level and above. Greatly enhanced corrosion was evident after temporarily raising the water to a higher level than before. In all cases it was build up of chloride ions to an unacceptable level that was the cause of deterioration. After extensive investigation it was decided that sacrificial cathodic protection was the most cost-effective long-term solution. Over 110 tones of aluminum alloy anodes were installed to protect approximately 350,000 m^2 of submerged reinforced concrete surface. Where the waterway was bounded by a reinforced concrete wall exposed to the atmosphere, a build-up of chloride ions had been detected on the dry face due to migration of seawater through the wall, and evaporation. This face was therefore sealed with an epoxy coating both to minimize evaporation, and to minimize oxygen ingress. In excess of 20,000 m^2 were epoxy coated.

The cathodic protection system has been monitored since installation, and over a period of 6 months, the steel potential has become -850 mV (Ag/AgCl reference electrode) or more negative at over 99% of the points monitored. The installed system is considered to be completely successful in arresting corrosion below the water level.

The portions of structures projecting above the water do not of course benefit from the sacrificial cathodic protection system. These areas were treated with a sealant designed to resist further ingress of chlorides. Over 350,000 m^2 of concrete surface were treated in this way.

Administration Building Concrete Foundations. The building is a five-story structure constructed of reinforced concrete. Two hundred fifty six (256) primary columns support the main building and additional four hundred eighty one (481) columns support the surrounding parking garage. Most columns are founded on single spread footings carrying load to soil strata one to two meters beneath. Surveillance has revealed varying degrees of corrosion in the columns immediately below or near grade surface. Chloride content tests confirmed contamination at the rebar location in excess of threshold limits. Although such contamination was confirmed for both columns and footings, concrete deterioration was observed to be limited primarily to the columns below ground, but above the footings.

Several repair solutions were initially investigated, but only two were considered attractive, as follows.

- Cathodic protection.
- Column encasement

Cathodic protection using impressed current offered the potential of a good solution. It was adopted and more than 100 columns received cathodic protection.

High cost, possible stray current, and the need for periodic monitoring for this rehabilitation method led to adoption of another repair method, which is less costly and does not need periodic monitoring. In this method the column portions located below grade are encased in a concrete mass reinforced with hoop bars. Only loose concrete was removed from the columns prior to placing the reinforced concrete encasement. The encasement is expected to slow down future corrosion and to maintain the load path. Expansive forces of corrosion will be restrained by hoop tension steel that will keep the surrounding concrete in compression, thus preventing deterioration and spalling of concrete.

This approach offers several cost and technical advantages over traditional patch repair and cathodic protection. Savings as much as 65% are realized by encasement compared to cathodic protection. Technically, the encasement also offers a long-term passive solution that protects that column and provides footing strengthening or equivalent replacement.

Underground Concrete Power Manholes. Severe chloride-ion-induced corrosion damage has occurred on some of the 2500 underground reinforced concrete power manholes at Madinat Al-Jubail Al-Sinaiyah. These manholes carry 34.5 - 115 kV cables and are part of the electrical power distribution network. They have an internal dimension of up to 8 m and are as much as 6 m below the groundwater table. After they had been about 6 years in service, a survey has shown that some 150 manholes needed urgent attention to prevent further structural damage that might affect the power distribution system on which the City depends.

Numerous options for rehabilitating the manholes were considered and evaluated and finally one method was chosen, which consists of constructing new manholes within the existing ones. The reconstruction methods specified fly ash blended cement and FBECR.

Shoreline Protection Concrete Structure. The structure is a 2 km long shoreline protection retaining wall comprised of tied-backs, and precast concrete wall panels with precast concrete cap beams and cast-in-place concrete top beams. The tie rods are protected by sacrificial cathodic protection. The concrete components were designed to have 50 and 75 mm concrete cover for cast-in-place and precast concrete elements, respectively. Fly ash concrete was used for the precast concrete wall panels. Water cement ratio of 0.4 was used in all concrete mixes. About ten years after the retaining structure was put into service, longitudinal cracks were observed on the top beam surface. These cracks were typical of those caused by reinforcement corrosion. No signs of concrete deterioration were observed in the precast wall panels.

Chloride content test performed on the wall components indicated a chloride front of 37 mm depth in the precast components, while chloride content in the cast-in-place top beam had exceeded the 0.3 percent corrosion initiation threshold limit (Acid soluble by weight of cement). The excellent performance of the precast members is attributable to the low concrete permeability due to the presence of fly ash and good quality control for production of the precast elements in the plant. The poor performance of the top beam is probably caused by improper concrete compaction and curing during original construction.

Buried Concrete Pipelines. Steel cylinder reinforced concrete (SCRC) pipes have been used in Madinat Al-Jubail Al-Sinaiyah for transmission of potable and reclaimed water. Inadequate corrosion protection measures during the installation of the pipelines have resulted in exterior corrosion of steel cylinders and pretensioning rods. This is more serious in the areas where the pipe were laid in highly saline soil, soils of low resistivity and in high groundwater table. Generally, the pipelines have performed very well and, after twelve years in service, only two failures of the pipes have been reported. However, corrosion surveys have indicated that the corrosion is active at many sites on the pipelines.

Rigorous examination of several rehabilitation options for extending and preserving the residual service life of the pipelines was undertaken. The Impressed Current Cathodic Protection (ICCP) technique has been determined to be an economical and effective rehabilitation method for these pipelines. The selection process included extensive review of available pipe repair data, field investigations, corrosion condition surveys, and Cathodic Protection field trials on the installed pipelines. The trials involved installation of ICCP and Sacrificial Anode cathodic Protection systems in field on existing pipe sections in different environs and monitoring the shifts in potentials and current requirements.

Concrete Transportation Structures. Head walls, dividing walls, and ceiling of multi-cell concrete culverts, as well as components of concrete bridges, were affected by reinforcing steel corrosion resulting in delamination and cracking of concrete. In the culverts, the deterioration occurred mostly at the entry and exit of the structures, however, some culverts soffits were also affected by similar deterioration. The bridges suffered most of the damage in the piers in areas located near and below grade level. The deterioration was mostly caused by chloride induced corrosion of reinforcing steel. Concrete deterioration also occurred due to mechanical damage by weathering as some of the structures are located over drainage channels carrying saline groundwater.

Repairs were performed by carrying out localized patching as part of continuing maintenance programs. In the areas were concrete deterioration is caused by reinforcing steel corrosion, the damaged concrete was removed to expose the corroding rebars and rebars were cleaned and coated. The area was then repaired and coated along with surrounding areas. Non-shrink gout, polymer modified mortars, as well as concrete made with OPC, and bonding agents were used for repairs. The concrete areas which suffered weathering damage were repaired using polymer modified repair mortar.

The earliest repairs to these structures were carried out more than 8 years ago. The repaired areas remain sound to date. However, some cracks were recently initiated in some of the areas near the repairs.

The patch repair technique has been used at Madinat Al-Jubail Al-Sinaiyah for repairing numerous other structures such as water storage concrete tanks, marine structures, underground inspection chambers, etc. with similar success.

CONCLUDING REMARKS

Many forms of corrosion repair options are available for reinforced concrete structures and the decision as to which would provide the best corrosion repair and protection to a structure over its required future life span is dependent on a number of conditions. For any particular problem, each method of control must be fully evaluated.

Partial or whole replacement and/or cathodic protection methods are often the most permanent solutions but may not be practical for all cases. For chloride contaminated concrete exhibiting corrosion damage, cathodic protection may be one of the most useful practical solution.

Case histories based on experiences gained in Madinat Al-Jubail Al-Sinaiyah with several concrete repair options were presented in the paper.

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