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APPLICATION OF AVAILABLE TECHNOLOGIES FOR PRODUCTION OF DURABLE CONCRETE

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ABSTRACT. This paper briefly discusses the primary causes of corrosion of the reinforcing steel as a result of ingress of chloride ions to the rebars. The available technologies that have been developed during the recent two decades to control the phenomenon of reinforcing steel corrosion and deterioration of the concrete structures are also presented accompanied with their advantages and limitations. These technologies include chemical additives to the concrete, use of corrosion resistant reinforcements, coating of the rebar or concrete, installation of cathodic protection, use of special types of cements, and chloride removal using non-destructive electrochemical techniques. This paper makes comparisons between these technologies in terms of their effectiveness, practicality, and cost.

1. INTRODUCTION

The Arabian Gulf region is considered one of the most aggressive environments in the world. As a result, early concrete deterioration is being noticed in numerous structures throughout the Eastern Province of Saudi Arabia. The primary cause of deterioration of these structures is attributed to corrosion of reinforcing steel due to chloride attack. Protection of concrete against chloride attack has been difficult due to poor quality aggregates, high ambient temperature, intense solar radiation, high humidity in coastal areas, brackish water, poor workmanship, insufficient enforcement of quality control measures in the batch plants, and frequent violations of common industry construction practices.

In addition, designers often overlook the need to address special measures needed to obtain durable concrete. Their concrete specifications are generally based on international standards developed for different environments.

This paper presents examples of the deterioration, causes and preventive measures available to counteract the problem. The paper briefly discusses the effects of the local environment and the role of materials on the deterioration of concrete and measures towards achieving impermeable concrete. Aggregates from different sources were tested. Various chemical and physical properties were evaluated and compared against international standards.
Several technologies and materials have been developed worldwide over the last two decades to prevent concrete deterioration from occurring. These technologies include:

1. Chemical additives such as corrosion inhibitors.
. Different types of reinforcing bars such as stainless steel and fiberglass reinforced plastics.
3. Rebar coatings such as epoxy and galvanized coatings.
. Installation of cathodic protection systems including impressed current and sacrificial anodes.
5. Special cements
6. Concrete surface treatments such as penetrating sealers and surface coatings.
7. Chloride removal by electrochemical methods

This paper provides an overview of the various aspects of these technologies and materials in terms of practicality, limitations, cost effectiveness and future outlook. The overview is based on extensive literature review, field and laboratory experience.

2. CAUSES OF DETERIORATION

Reinforced concrete fails in several ways. In early life, plastic deformation and shrinkage cracks allow gases and chemical contaminants, along with moisture and oxygen, to penetrate the concrete. In later life, surface deterioration occurs due to sulfate attack and alkali reactions. Depending on many factors, it is only a matter of time in a harsh environment before chlorides penetrate the concrete, attack the reinforcing steel and initiate the corrosion. The corrosion products (rust) occupy a much larger volume than the original steel and the resulting expansive forces crack and spall the concrete (ref. 1). Protection of concrete against chloride attack has been difficult due to the aggressive environment, unskilled workmanship, lack of proper QA/QC program and common violations of the Industry Practice.

Moreover, aggregates available in the Eastern Province of Saudi Arabia are not ideal for high quality concrete with relatively soft limestone being used as coarse aggregate and poorly graded dune sand being used as fine aggregate. Samples were obtained from the batch plants in the Eastern Province (E.P.) and the Central Province (C.P.) of Saudi Arabia and tested in the laboratory. Table 1 shows the percentage of samples which meet the industry standards. These results show the inability of the local aggregates to meet the soundness and sulfate limits established by industry standards. Applying the international industry standards will prohibit the use of most of the aggregates in the two Provinces.

Furthermore, ground water is generally too brackish for use as mixing or curing water (ref. 2). This results in a contaminated concrete.

Table 1 Local aggregate

Property	E. P.	C. P.	I. S. Limits
Absorption	100 %	100 %	2.5 (BS 5337)
Abrasion	100 %	100 %	50 (ASTM C33)
Acid soluble chlorides	95 %	70 %	0.03 (BS 1881)
Acid soluble Sulfates (SO3)	55 %	55 %	0.4 (BS 1881)
Soundness	90 % (20 mm) 37 % (10 mm)	100 % (20 mm) 74 % (10 mm)	18 (ASTM C33)

3. PREVENTIVE TECHNOLOGIES

Various corrosion protection technologies have been developed to arrest and control the chlorides-induced corrosion of the reinforcing steel. Of those technologies, some will postpone the problem of corrosion, some will control the corrosion phenomenon and the use of corrosion resistance materials as reinforcing steel will eliminate this problem. However, each of these technologies has its own limitations which should be considered during the selection of the preventive measures.

3.1 Chemical Additives

Numerous corrosion protection chemical additives that include admixtures and corrosion inhibitors have been developed over the last 20 years to delay and postpone the occurrence of the corrosion of the reinforcement of concrete structures.

3.1.2 Corrosion Inhibitors : Corrosion inhibitors for concrete are materials added in small amounts to the concrete mix or injected into the concrete element to reduce or stop corrosion (ref. 3). These materials function on the anodic surface of the reinforcing steel by reforming the passive film on the reinforcing steel and converting ferrous oxide to ferric oxide. This ferric oxide (Fe2O3) serves as a barrier which prevents iron ions from leaving the reinforcing steel.

Limitations : Even though some of the corrosion inhibitors gave promising results (such as calcium nitrite) in protecting the reinforcing steel in contaminated concrete, the following should be considered for applying and adding concrete inhibitors to the concrete matrix:

- The ratio of chlorides ions to that of inhibiting agent is critical to preventing an imbalance that can result in pitting corrosion of the reinforcing steel (ref. 4).

- Anodic inhibitors require high concentration for full and effective protection of reinforcement against corrosion (ref. 5).
- There is some concern about reduction of the concrete compressive strength due to the addition of these materials (ref. 6).

Cost : Corrosion inhibitors can add up to $ 40 to the cost of one cubic meter of concrete.

3.2. Different Types Of Reinforcing Rebars

3.2.1. Fiber Reinforced Plastics : Fiber Reinforced Plastic (FRP) is one of the most promising new technologies transferred to civil engineering applications from the aerospace, automobile and sports industries. FRP consists of fibers, usually glass, imbedded in a plastic resin matrix (ref. 7). FRP reinforcements provide durable concrete structures that are free of deterioration caused by corrosion of steel. Commercially available FRP reinforcement are Glass Fiber Reinforced Plastic (GFRP) , Carbon Fiber Reinforced Plastic (CFRP) and Aramid Fiber Reinforced Plastic (AFRP). GFRP was first used in the concrete industry in the mid-eighties in West Germany for prestressing experimental bridges. Several pedestrian and road bridges were then constructed in Europe, Japan, China and the United States during the last decade using GFRP, CFRP and AFRP as trusses, cover plates, box girders and prestressing tendons (ref. 8).

FRP reinforcements are lighter and more corrosion resistance than steel. CFRP and AFRP are three times more fatigue resistant than steel. FRP has a low axial thermal expansion coefficient and has excellent dielectric properties (ref. 8, 9).

Limitations : Long term strength of FRP reinforcements can be lower than short term static strength and it is affected by ultraviolet damage and temperature. Pullout tests showed that the bond between FRP rebars and the concrete is about two-thirds of that obtained between steel rebars and concrete (ref. 9, 10). A 26-month study was sponsored by the Florida Department of Transportation in cooperation with the U. S. Department of Transportation to investigate the durability and the possibility of using S-2 fiberglass instead of steel reinforcement in a marine environment. The results of this study showed deterioration of the GFRP due to moisture attack. The formation of hydroxyl ions in the concrete pore solution due to combination of the moisture with the alkalies present in the concrete attacked the basic silicon-oxygen-silicon structural network of glass which resulted in rapid and severe strength loss of specimens made with GFRP. Moreover, the absence of visual signs of deterioration in the GFRP concrete samples makes them potentially more dangerous in structural applications when compared to the steel reinforcement (ref. 11).

Cost : GFRP cost 5 to 10 times the cost of conventional steel.

3.2.2. Stainless Steel Reinforcement : Stainless steels have excellent resistance to corrosion. All true stainless steels contain a minimum of about 12% Cr (chromium) which permits a thin protective surface layer of chromium oxide to form when the steel is exposed to oxygen. Results on the corrosion resistance of stainless steel which were carried out in Denmark showed the ability of 304 & 316 stainless steel to resist corrosion respectively 10 & 16 times higher than the black steel (ref. 12). Results of a seven-year study at King Fahad University of Petroleum & Minerals comparing different types of reinforcing steel showed the superior performance of stainless steel claded reinforcing steel. After 7 years of embedment in concrete containing 19.2 kilograms of chloride (added as sodium chloride through the mix water) per cubic meter of concrete, no sign of corrosion was observed on any of the stainless steel bars tested (ref. 13). According to Jha (ref. 14), the presence of chromium in stainless steel helps in a spinel oxide layer ($FeO.Cr2O3$) formation which is a poor conductor of electrons thereby reducing the corrosion rate. The compact dense rust layer produced prevents the ingress of oxygen and water to the rebar.

Limitations : The very high cost of stainless steel prohibits its use on a large scale in the construction industry.

3.3: Rebar Coatings

3.3.1. Galvanized reinforcement : Galvanized reinforcement has been used in concrete construction since the 1930's. The steel reinforcement is hot dipped in zinc (Zn) at 460 degrees Centigrade. In this process steel reinforcement will be galvanized by zinc coating. Galvanized steel will be protected against corrosion by the sacrificial coating which corrodes before any of the underlying steel corrodes. The usual corrosion product of Zn (zinc oxide) occupies 50% more space than the metal, in contrast to the 100% or more increase for rust. Moreover, Zn is passivated in the concrete matrix and can remain passivated to lower pH level than that which destroys the passive film surrounding the black steel and causes corrosion.

Galvanized reinforcement can tolerate chloride ion levels in concrete at least 2.5 times higher than the levels which cause corrosion of black steel (bare steel) in equivalent concrete and exposure conditions. Galvanized reinforcement has the ability to increase the period for initiation of the corrosion process 4 to 5 times when compared to black steel (ref. 15).

Limitations : There are some concerns about the performance of galvanized steel in extreme corrosive environments and highly contaminated concrete. Under severe conditions, the corrosion product of galvanized steel was found to be zinc hydroxychloride II (Zn5[OH]8Cl2.H2O) which occupies 260% more space than Zn and produces much greater stresses than most forms of rust (ref. 15, 16).

Cost : Galvanized rebar cost is twice the cost of conventional steel.

3.3.2. Fusion bonded epoxy coated rebars (FBECR): FBECR was first introduced in the United States in a Pennsylvania bridge in 1973 in response to the corrosion problems in the bridges caused by deicing salts. Since that time, the use has increased steadily into other structures such as water cooling towers, sewage treatment plants, parking garages and marine structures. Considerable information and data are being gained from the wide and growing use of this material as an anti-corrosion of rebar alternative. The field and laboratory performance over the past 20 years has been very good. A field study of 22 bridge decks in Pennsylvania indicates good performance over ten years (ref. 17). None of the 11 decks reinforced with epoxy coated bars showed any visual signs of deterioration. Four of the 11 decks with uncoated bars showed concrete deterioration caused by corrosion of the reinforcement.

Chris (ref. 18) found that the risk of corrosion of epoxy coated reinforcement cages in precast concrete segmental tunnel linings extremely low and that any corrosion developing at holidays will be several magnitudes less than what would have developed for uncoated reinforcement under similar conditions. Laboratory examination of FBE coated rebars shows similar results (ref. 19, 20, 21). Good corrosion resistance was obtained with even non-specification epoxy coated rebar (ref. 22). The use of FBECR in the Kingdom of Saudi Arabia was introduced in the late 1980s. Since that time, several local plants were established to provide FBE coated rebar to the users in the Kingdom at competitive prices.

Limitations : Despite the excellent corrosion protection performance of epoxy coated reinforcement in most situations, the effectiveness of epoxy coating in very severe environments has been recently questioned (ref. 23, 24). In the late 1980s, several bridges in the Florida Keys had suffered severe corrosion. As a result of these set backs in the performance of FBECR, U.S. government agencies have been reevaluating the practice of epoxy coating and have lowered their expectations for long-term performance. This is primarily because the coating has naturally occurring holidays and may be damaged during transportation and fabrication. Consequently, a great deal of emphasis is placed on the careful handling and storage of epoxy coated reinforcement to minimize abrasion and mechanical damage. Touch-up of damaged areas of the coating is usually required. Ideally, the rebar should be prefabricated prior to coating which will minimize the need for the touch-ups. This process is much more expensive, but the final product is more likely to be more effective against corrosion. A task group of a committee of the American Society for Testing and Materials completed work on a new standard geared to harsh environments in January 1994.

The authors believe that a need exists to research a new family of environmentally friendly rebar coatings that function as passivation-type coatings which will protect steel from corrosion even when there are holes through the coating.

Cost : Coated rebar adds up to 60 % to the cost of conventional steel.

3.4. Cathodic Protection

Cathodic Protection (CP) is a multi-discipline technology that was transferred to the field of reinforced concrete after it had been used widely in preventing corrosion of buried pipelines, chemical plants, underground storage tanks, and marine steel structures. However, the application of this technique to protect concrete structures, other than bridges, is still in the development stage. The first use of the CP technique for protection of reinforced concrete from corrosion was for the Sly Park bridge in California in 1973. As a result of the apparent success of this project, the Federal Highway Administration (FHWA) issued a directive permitting its use in 1976. Although technically possible , the C.P. system for garage-type structures was difficult to install, greatly increased the dead loading, and reduced clearances. The practical use of CP on non-bridge concrete structures started in the mid-1980s when a newer generation of CP systems eliminated many of these construction problems of the conductive asphalt system (ref. 25).

3.4.1. Principle of cathodic protection : The principle of CP is to inhibit the corrosion process by causing a direct electrical current to flow to the steel rebar (cathode) so that all points on the surface are polarized to a potentially more anodic than the most anodic point on the steel rebar. The rebar then becomes cathodic with respect to an external anode (ref. 26).

3.4.2. Application methods : There are two methods of applying the current to the protected concrete namely, sacrificial anodes or an impressed current source. The main shortcoming with the use of a galvanic anode system in concrete is its insufficient power to force the electrons to flow to the cathode (steel rebars) due to the high resistivity of the concrete cover (ref. 27). This paper will elaborate on the use of Impressed Current Cathodic Protection (ICCP) because of its wider use.

3.4.3. Limitations of ICCP : One of the most controversial aspects of the cathodic protection of concrete reinforcement is the protection criteria. Until the year 1990, no criteria was adapted by any of the industry standards. In 1990, the National Association of Corrosion Engineers (NACE) adapted the 100 mv polarization development/decay and the E log I analysis as a guideline for protection of reinforcing steel (non prestressed) in atmospherically exposed concrete structures with a distributed anode system only (ref. 28). The protection criteria is empirical and based on experience. Limitations and uncertainty are associated with this criteria.

The effectiveness of the anodic systems varies from material to another. Bright (ref. 29) tested the performance of 11 anodic systems and only one of them satisfied the NACE criteria. He recommended testing anodic systems to measure their potential performance before installing them.

ICCP may accelerate the alkali silica reaction if high current density is applied (ref. 30) and may also degrade the bond between the reinforcing steel and concrete (ref. 31). The potential of the steel must be maintained within a narrow range. If it is too positive, corrosion can occur. If it is too negative, anode life will be shortened and hydrogen may be evolved at the cathode causing embrittlement of the reinforcement. The use of CP to protect reinforcing concrete structures from corrosion needs periodical monitoring and maintenance of the system. Moreover, the performance of the protection criteria and the effectiveness of the anodic system and its expected life may vary with environmental conditions.

Cost : Cathodic protection costs $150 per square meter of concrete. Maintenance cost is not included.

3.5. Special Cements

3.5.1 Calcium Aluminate Cement : Calcium Aluminate Cement (CAC) was originally developed as a sulfate resisting cement, but other problems precluded its use for this purpose. Unlike Portland and modified Portland cements, the principal cementing compounds in CAC are monocalcium aluminate. CAC possesses many unique properties such as high early strength, hardening even under low-temperature conditions and superior durability to sulfate attack.

Limitations : Several structural failures were reported where concrete containing CAC had been used. The failures which were attributed to gradual loss in strength limited the use of this cement for structural applications. The hydration product of CAC (C2AH8 or CAH8) is unstable, especially in hot and humid conditions. The instability of the hydration product and its conversion to another stable form (C3AH8) is associated with a large increase in porosity and, therefore, a corresponding decrease in strength. Moreover, the stable form is sensitive to sulfate attack. The desired sulfate resistance will diminish and the strength loss due to the conversion process will be aggravated by subsequent sulfate attack (ref. 32, 33). In most countries, CAC is used for making castable refractory lining for high-temperature furnaces.

Cost : Calcium Aluminate Cement adds about $110 to the cost of one cubic meter of concrete.

3.6 Concrete Surface Treatment

Concrete surface treatment can be achieved by the use of surface coating or the application of penetrating sealers. Surface coating and penetrating sealer materials will prevent the ingress of harmful salts, moisture and oxygen from reaching the reinforcing bars. Moreover, the penetrating sealers will allow the evaporation of the trapped moisture in the concrete.

Sealers which can penetrate the surface of concrete gave very promising results when applied to contaminated and non-contaminated exposed concrete structures. A laboratory study that investigated the performance of different types of penetrating sealers showed the superior performance of silane based sealer (40% solid by weight) to resist water absorption, thermal cycling, abrasion, and to allow the internal moisture to evaporate (ref. 34). Vassie (ref. 35) found that the application of Alkyl alkoxy silane on chloride contaminated concrete reduced the corrosion rate by 37% when compared to untreated samples.

Limitations : Concrete coating materials should be applied while the concrete surface is dry. An important issue that needs to be considered with the use of the coating materials is the surface preparation of the concrete. In the environment of the Arabian Gulf, the thermal cycling and the resistance of the coating materials to high temperatures and to temperature fluctuations should be considered. Life expectancy varies between different coatings and penetrating sealers.

Cost : Average cost of coatings is about $20 per square meter of concrete. Penetrating sealers cost about $3 per square meter.

3.7. Chlorid Removal Electrochemically

The feasibility of using electrochemical techniques to remove chloride ions from concrete and thereby arrest or reduce corrosion of embedded reinforcement was investigated in two major studies in the 1970s (ref. 36, 37, 38). The process consists of applying an anode and an electrolyte to the surface of a reinforced concrete structure and passing a direct current between the anode and the reinforcing steel which acts as a cathode. The technique is similar to the application of cathodic protection but differs in two important respects: the anode is temporary, and the current density applied is one hundred times that used in most cathodic protection installations. However, if successful, the technique has the important advantage over cathodic protection in that it does not require regular monitoring and maintenance.

There was little research in North America on electrochemical removal techniques until the Strategic Highway Research Program (SHRP) started testing them. A project was defined within SHRP to examine the affects and determine the feasibility of electrochemical removal technique and, if feasible, develop procedures for use in the field (ref. 39). SHRP Contract C-102A, Electrochemical Chloride Removal and Protection of Bridge Components was awarded in May 1988. The results indicate that chloride removal at lower current densities (0.1 to 0.2 amp/sq. ft.) are able to successfully remove the chloride from the area immediately around the rebar without causing damage to the concrete. In addition, the treatment results in a build-up of hydroxide ions at the steel surface which plays an important role in arresting corrosion. The study found the process both feasible and technically practical.

Limitations : High current densities used in the earlier studies were considered impractical. There were concerns of undesirable effects on the concrete and steel such as an increase in permeability, reduction in bond of the reinforcement, migration of alkalis to the reinforcement, and the possibility of cracking induced by the high temperature developed in the concrete. The process does not remove the total chloride present but complete removal may not be necessary. Finally, the generation of chlorine gas from the anode presents a safety hazard. The study suggested that the electrolyte be maintained at a basic pH to prevent generation of chlorine gas (ref. 39).

Cost : The chloride removal process is difficult to judge until a greater data base of experience is logged. A recent survey indicates the cost to be about $200 per square meter of concrete.

4. CONCLUSIONS

Concrete deterioration due to chloride attack is a serious problem in the Arabian Gulf. Concrete structures designed 30 to 40-year lives typically need major maintenance repairs in less than 10 years. The cause of this phenomena is attributed to the quality of materials used, the severity of the environment, quality control during concrete production and finishing, and poor workmanship. Accordingly, design and construction specifications were updated to produce a higher quality and more durable concrete. Furthermore, to combat the aggressive environment of the Gulf, several protective alternatives to protect the structures from chloride attack and extend their service lives were evaluated. More protective layers might be necessary to achieve the required protection in corrosive service. These measures vary in practicality, effectiveness and extension of service life. These protective alternatives should be considered as additional measures and not substitutes for good quality concrete.

In addition to their technical limitations, the designer must also consider their cost effectiveness. The cost estimates provided in this paper are approximate and are intended to give a comparative evaluation of the various systems. The actual cost will vary depending on the structure type, size and location.

The conclusions presented in this paper are based on our knowledge and understanding of the performance of these systems in similar environments and/or laboratory controlled conditions. It is believed that continuing research will produce more cost-effective materials that can improve the durability of concrete structures in this part of the world.

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