

Fig. 3. Effect of the molar Na₂O-to-SiO₂ ratio on Compressive Strength



Fig. 4. Slump values for mixtures 1 to 5

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Effectiveness of Anti-Corrosion Products for Reinforced Concrete Exposed to United Arab Emirates Environmental Conditions

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Synopsis:

A long-term research study on anti-corrosion products for reinforced concrete exposed to aggressive environmental conditions was initiated in 1990. The performance of products was evaluated through accelerated laboratory testing and natural site exposure conditions as tidal zone, above ground and below ground. An exposure site on the Dubai creek shore is designated for long term performance testing at different ages extending up to ten years. A series of physical and electrochemical testing were performed in three phases. The prime objective of the first phase was to assess the performance of the various products, and to assess the practical value of different electrochemical test methods. The focus of the second phase testing shifted towards a more comprehensive evaluation of the test methods. The interim results have been presented at different international conferences. The focus of third phase, which was performed in early 2000, was to observe the actual extent of corrosion sustained by the rebar. This paper presents the final data to substantiate conclusions relating to ingress of chlorides for the various exposure conditions (threshold values), provides recommendations for corrosion monitoring for new structures and test methods for evaluating products and future research requirements.

<u>Keywords</u>: chloride ingress; concrete; corrosion; electrochemical test; inhibitor; threshold

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INTRODUCTION

Dubai Municipality had a long-term research programme since December 1990 involving reinforced concrete specimens placed at an exposure site on the Dubai creek shore at the Al Jaddaf area. A series of physical and electrochemical testing on selected specimens, which were not in a state of structural stress, were performed to establish the effectiveness of anti-corrosion products.

Products Characteristics

The characteristics of these products as declared by their manufactures are as follows:

Product I	A pure inorganic soluble silicate in powder form
Product 2	An aqueous suspension of polymerglobules with a
	hydrophobic pore-blocking ingredient
Product 3	An aqueous suspension of ammonium stearate and
	hydrocarbon resins.
Product 4	A product of about 92% amorphous silicon dioxide
Product 5	A penetrating surface coating which becomes part of the concrete chemistry.
Product 6	An amalgam of different chemicals in powder form.

The identification of the products are replaced by numbers to protect their commercial name.

Recent Advances in Concrete Technology 121

PARAMETERS

Considering the site practices prevalent in the local construction industry with regard to quality control on site and workmanship skill levels, the performance of the proposed products are evaluated by using the following parameters:

- 1. Exposure environment
 - tidal zone (lying on beach -- submerged at high tide)
 - below ground (covered with 300 mm of soil)
 - above ground (on racks in air)
- 2. Mixtures concrete water cement ratio
 - Mixture A -- 0.44 W/C (high quality mixture)
 - Mixture B -- 0.60 W/C (low quality mixture)
- 3. Electrochemical testing by specialist laboratories
 - A specialist laboratory performed a series of physical and electrochemical testing on selected specimens.

PROGRAMME

The testing consisted of three phases

The First Phase

The first phase of testing was performed in 1995 and reported in January 1996. The prime objectives of that testing were to assess the performance of the various corrosion control 'products' incorporated in the specimens, and to assess the practical value of different electrochemical test methods:

- i) Cover measurements
- ii) Continuity measurements
- iii) Half-cell potential measurements
- iv) Linear polarisation resistance testing (corrosion rate measurements)
- vi) AC impedance measurements
- vii) Corrosion current measurements
- viii) Resistivity measurements

The results of the studies have been published in four research papers [1-4] contributed at regional and international conferences. Test results produced were used to assess the effectiveness of various products for inhibiting the corrosion of reinforcing steel in concrete. Among the six products used in the study, two were found to be totally ineffective (products 1 & 6) and they were discontinued.

The Second Phase

The second phase of testing was performed in late 1997 and early 1998. The focus of this test phase shifted towards a more comprehensive evaluation of the test methods, by evaluating the correlation between them. As such, it was necessary to evaluate the extent of corrosion actually sustained by the rebar and compare these observations with the electrochemical test data.

- i) Half-cell potential measurements
- ii) Resistivity measurements
- iii) Corrosion rate measurements (linear polarisation resistance testing)

The Third Phase

The third phase of testing was performed in early 2000. The testing programme was applied to the reinforced concrete specimens Fig. 1. The specimens were taken from the same group of specimens tested during Phases 1 and 2. Non-destructive testing was followed by removal of reinforcement and examination of the rebar. The focus of this testing was to collect a final set of measurement data, followed by destructive testing to observe the actual extent of corrosion sustained by the rebars. Each specimen consisted of four longitudinal rebars tied together with rebar links near each end of the specimen such that the concrete cover varied on each rebar. A significant aspect of the specimen construction was that the longitudinal rebar were positioned on the inside of the link bars which meant that the links had substantially less cover. This significantly affected the results of the exposure, particularly for the uncoated rebar. Two specimens were selected from each of the above Exposure / Mixture / Product combinations and, once prepared, a series of electrochemical tests were applied, consisting of the following:

- i) Continuity verification
- ii) Half-cell potential profiles
- iii) Chloride ingress tests

For each specimen tested, the rebar having 'Most' / 'Least' concrete cover was individually tested. For "least cover" the range was from 15 mm to 30 mm while for "most cover" the range was from 30 mm to 65 mm as shown in Fig. 2.

OBSERVATIONS OF SPECIMEN AND REBAR CONDITION

Classification System

Insofar as the electrochemical testing is concerned, the purpose of the condition survey was to 'classify' the extent of corrosion damage sustained and study its correlation to the electrochemical test data. Following a detailed study of

the condition survey data obtained, a classification system was developed as follows:

- Class 1 Negligible: Specimens exhibiting limited concrete surface discoloration by corrosion of the rebar (i.e. <20%) and no visible signs of corrosion of the rebar deterioration.
- Class 2 –Superficial: Specimens exhibiting corrosion but no apparent metal loss. The limits of the rebar surface area corrosion were 20% to 40%.
- Class 3 -Moderate: Specimens exhibiting 40% to 60% rebar surface corrosion, but no significant metal loss.
- Class 4 -High: Specimens exhibiting 60% to 80% rebar surface corrosion and/or metal loss.
- Class 5 -Severe: Specimens exhibiting >80% rebar surface corrosion and/or metal loss causing large cracks and delaminations in the concrete.

Whilst the classification system above was developed specifically for the main rebar in the specimens, variations of it were also applied to the Concrete. Table 1 shows the extent of metal loss from the rebar and links. This was measured via the reduction in diameter in the bars. Initially the rebar, and links diameter were 12 mm and 10 mm respectively. The $D_{Reduction}$ columns in Table 1 show the smallest diameter along the length of the rebar as per the fallowing calculation method used to calculate the reduction in the bar diameter

The calculation assume that the metal loss is evenly distributed around the diameter of the bar.

Length to weight ratio: L/W ratio (kg/m) = weight of rebar specimen / Length of rebar specimen

For any given two specimens:

$$\frac{Area_1(m^2)}{Area_2(m^2)} = \frac{(L/Wratio_1)/\rho_{steel}}{(L/Wratio_2)/\rho_{steel}} = \frac{L/Wratio_1}{L/Wratio_2}$$

Hence:
$$r_2 = \frac{r_1}{\left[(L/Wratio_1)/(L/Wratio_2) \right]^{1/2}}$$

Where: r_1 = Initial radius r_2 = Final radius

Therefore reduction in nominal diameter:

$$(r_{1} - r_{2}) = r_{1} \left[1 - \frac{1}{\left[(L/Wratio_{1})/(L/Wratio_{2}) \right]^{1/2}} \right]$$

DISCUSSION OF TEST RESULTS

General Comment

The parameters considered in the study are compressive strength, water absorption, water penetration, and chloride ingress. Among these, chloride ingress is the prime deciding factor influencing the corrosion of reinforcing steel in concrete. This ingress is dependent on the water absorption and water penetration of concrete. These parameters are functions of the characteristics of the pores in the concrete such as their volume, size, distribution and continuity. Water absorption measures the volume of pore space in concrete, while water penetration depends on the permeability of concrete which is not only a function of its porosity but also depends on the size, distribution and continuity of pores. So, introduction of pore blockers into the concrete mixture would affect both water absorption and water penetration. From this, it is to be expected that the lower the absorption and penetration, the less chloride penetration should be. However, comparison of the test results published in [1 - 4] shows that this is not the case.

Possible explanations could be due to variation in the salinity concentration levels surrounding the specimens in the below ground exposure and variation in the salinity deposition on the specimens due to alternate wetting and drying of specimens subjected to inter-tidal movements. With respect to above ground exposure conditions, the permeability may be high but there is not much chloride in the environment available for penetration. Thus results do not follow expected trends, and we find no rational basis for deriving co-relations.

All corrosion prevention products / techniques mentioned above are intended as a supplement – and are not intended to be a substitute – for concrete quality. Proper mixture, cover depth, compaction and curing are equally important and effective in halting rebar corrosion.

Environments

The potentials measured in the specimens above ground are much less 'active' than those of the tidal zone & below ground specimens. The specimens above ground exhibited potentials (-380 to + 40) mV Ag/AgCl range, while those of the tidal zone and below ground typically fell in the (-200 to - 650) mV Ag/AgCl range. The more 'active' potentials in the tidal zone & below ground specimens are attributed to higher chloride concentration owing to direct exposure to salt water / saline soil, and to the water saturation of these specimens which would reduce oxygen availability in these exposures.

Exposure

The tidal zone and below ground exposures yielded similar results both in terms of electrochemical testing and sustained corrosion. Owing to their direct immersion in highly saline water / soil, the extent of corrosion in these exposures was high. In contrast to the tidal zone and below ground specimens, the specimens exposed above ground are not affected as yet. This difference clearly illustrates the need to consider exposure when designing reinforced concrete structures.

Potential Measurements

The potential measurement data correlated well and consistently with the corrosion classification data. It is a relatively easy test method to implement, is well understood and should definitely be applied in assessing the condition of reinforced concretes structures. Referring specifically to corrosion potential over 1995, 1998 & 20000 test programs, there is a direct correlation to the guidelines provided in ASTM C876-91. The limitation of the method is that rebars will not exhibit active potentials until the chloride has ingressed through the cover.

Chloride Penetration Measurements and Mixtures

The study included the correlation of the electrochemical test results with chloride ingress tests. These tests were performed on the same specimens as were employed for the electrochemical testing. The test data indicates the chloride levels at three depths (i.e. 0-15 mm, 15-30 mm & 30-45 mm). The results in most cases indicated that generally the chloride content diminished with depth consistent with ingress from the outside environment.

With the mixture A results, products 2, 4 & 5 had noticeably lower chloride ingress. The difference in the mixture B results is less distinct which highlights the importance of concrete quality. For the purpose of correlation, the average chloride concentration at the 30-45 mm depth was employed. The data provided by this operation correlated well with the corrosion classification and potential data.

The difficulty with this test is the need to drill holes in the concrete surface to collect dust for analysis. It is therefore a destructive test and the analysis can be costly. It is not a practical test to repeat in a close grid on the surface of reinforced concrete structures.

The advantage of the data provided by this test is that it provides a measure of chloride ingress before it reaches the steel. Therefore, the results of this test at a limited number of locations and in conjunction with potential measurement data can provide a very meaningful picture for corrosion assessment. The potentials of both

mixture A & mixture B specimens were in similar ranges for each condition due to the fact that they have reached the same level of corrosion.

Pore-Blocking Products

The efficiency of these products is best tested by their response to the most severe environment, namely the tidal zone. All the products showed less-electronegative potential readings than the control specimen. Overall, Product # 4 showed the lowest active potential readings [3 - 4] The differences in potential were not sufficient to provide product rankings.

Visual Inspection

Visual inspection was performed from time to time to check the physical conditions of the specimens at exposure site. This consisted of noting of rust stains, cracking, spalling, etc. Some of the specimens which did not show any signs of distress in the first year of exposure did so in the second and third year. This applies to all specimens with pore blocking products, and the control specimens placed in below ground and tidal zones. At the end of ten years of exposure, the above ground specimens containing pore blockers and the control were found to be in satisfactory condition with no signs of corrosion activity for both mixtures. Only in some specimens of mixture B, rust stains were noticed at random positions

THRESHOLD CHLORIDE CONTENT

The threshold chloride content for reinforced concrete structures can be briefly described as the chloride ion concentration for which the rebar surface is depassivated and actively corroding, thus resulting in metal loss of the rebar and eventually deterioration of the given structure. From the data obtained in phase three testing, there are three approaches by which threshold chloride levels may be determined. Some of the products (particularly the admixtures) can affect the properties of the concrete and these must be investigated separately.

The above ground specimens provide the best conditions (electrical and physical) for determining the threshold chloride content levels for the following reasons:

- i) The above ground specimens were atmospherically exposed specimens. The specimens were not saturated with chlorides, as in the tidal zone specimens.
- ii) Other factors that could cause 'active' steel potentials were minimized.

iii) Initiation of corrosion can be seen in some specimens which can be used to indicate the chloride levels required for initiation of corrosion. Most of the specimens in the below ground and tidal zone environments had already undergone deterioration due to corrosion.

Approach I

The first approach is dependent on the ASTM C 876 values for indicating corrosion activity. It is not indicative of the rate of corrosion, which is of key importance in determining the extent of damage. This approach is to use ASTM value of -350 mV CSE as the electrochemical potential at which steel is activated. By applying this criteria to electrochemical data of the specimens, the chloride concentration at which corrosion is occurring can be determined. The specimens with rebar potentials closest to -300 mV Ag/AgCl being more 'active' may be experiencing corrosion activity and therefore may have likely attained chloride threshold levels. Product # 2, in both mixture A and mixture B had recorded potentials closest to -300 mV Ag/AgCl with a chloride level of 0.028% for mixture A and 0.014% for mixture B by mass of concrete.

Approach II

The second approach used the physical condition of the above ground specimens as indicative of the initiation of corrosion. Corrosion of rebars eventually physically manifests itself as deterioration of the specimen. The specimens that exhibit any signs of deterioration have experienced corrosion activity induced by chloride ingress, and therefore may contain threshold concentration levels of chlorides. The specimens of product 4 show main bar and link bar with more than 60% of the rebar as being affected by corrosion. The data indicate that chloride content of 0.021% by mass of concrete is sufficient to cause physical deterioration of the specimen.

This method is more pragmatic approach in that it indicates the minimum chloride concentration level at which physical deterioration may occur in the specimens. However, it addresses the chloride content issue after the damage becomes visible rather than at the exact moment at which corrosion begins. This approach is to use the physical condition of the specimens as indicative of the initial and progression of corrosion. Any physical indication of corrosion in the form of staining, cracking or spalling or rebar cage condition, in an otherwise sound specimen, is indicative of the threshold chloride concentration having been reached.