# Structural Rehabilitation of a Chloride Contaminated Concrete Silo From View Point of Durability

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Synopsis
For structural rehabilitation of a silo in the Azores Islands, a multiple strategy was adopted with a view to minimise the negative effects of local repair in order to achieve extended durability.
A full diagnosis was carried out before the work started. The quality of execution was strictly controlled, corrosion-monitoring systems were installed in the zones repaired as well as in the other zones to assess the effectiveness of the solution in the long run.
Corrosion inhibitors were used in order to protect both repaired and non-repaired areas.

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## INTRODUCTION

The silo, a reinforced concrete structure completed by the slipform method in 1980, consists of a 62 m high equipment tower and a battery of 12 cylindrical bins, 6.5 m in diameter and 50 m high.

The exposed external surface amounts to 6000 $m^2$, and no protecting coating or painting was originally considered. The structure stands about 100m from sea, in a windy and moisture laden site, with periods of large temperature cycles, almost permanently under sea spray conditions.

The silo was constructed using very porous volcanic aggregates and beach sand.

For already some years, marks of significant deterioration have been noticed, mainly widespread concrete spalling owing to corrosion of reinforcement. In 1986 and 1992, some deteriorated zones were repaired using proprietary cement-based repair mortars and painted.

In 1994 some other zones were subjected to repairs with plain cement-rich mortars. These operations did not stop the deterioration process, that continued to develop with growing intensity (left side picture 1).

## CONDITION SURVEY AND ASSESSMENT

Faced with the low durability of the repairs, the Owner decided to order a more complete and accurate analysis of the anomalies in order to support a decision on the full rehabilitation of the structure.
By sampling, twenty-four external and two internal zones were tested, located at different levels in the cells and equipment tower. The places chosen showed different degrees of deterioration so that comparisons could be established.
It is important to study separately the inner and the exterior surfaces of concrete since the exposure conditions were quite different.

The following tests were carried out:

- Detection of reinforcement, and measurement of cover thickness
- Determination of depth of carbonation
- Evaluation of risk of active corrosion
- Determination of chloride content at several depths
- Ultrasonic tests
- Rebound tests
- Simple compression tests on concrete cores
- Concrete petrographic analysis
- Absorption and capillarity tests on concrete specimens
- Permeability tests on concrete specimens

The analysis of the main results obtained in the **external surfaces** of the structure is as follows:

The thickness of the reinforcement cover varies significantly. The mean thickness values range from 16 to 35 mm, in general, with about 30% of values in the 26 to 30 mm range.

The depth of carbonation ranged from 10 to 65 mm, that points to the marked heterogeneity of the concrete, even in the same test zone. More than half the values obtained (about 62%) correspond to 20 to 35 mm depths. In 75% of the cases in which rebars were exposed, the carbonation depth was found to equal or exceed the thickness of the cover.

Chloride content is high in the cement mass, 0,6% to 1% of cement mass at reinforcement depth (chart 1). Taking into account the results of the determination of chloride content at different depths, it was concluded that the high chloride content obtained on the external side is mainly due to the diffusion of the air-borne chlorides of the salt-saturated marine environment.

The results obtained through measurement of electric potentials show that the risk of corrosion is minimum only in three zones. In the other zones most results are not conclusive at the measuring points, i.e., a 50% probability of occurrence of active corrosion was found.

In general, concrete is very heterogeneous at the surface. In some cases, corrosion brought about a marked reduction of the section of reinforcement. From the point of view of strength, concrete is heterogeneous, with low strength in some zones and high strength at other places. Thus, concrete could not be fitted into a single class. On the average, its compressive strength was 25 Mpa;

Concrete had a w/c ranging from 0.35 to 0.50 and had high porosity. Microcracking makes the penetration of aggressive agents easy as well as their mobility into the concrete mass;

From the point of view of durability, the concrete can be classified as of poor to medium quality and deterioration affects large areas of the silos.

Analysis of the main results obtained from tests on the **internal concrete surfaces**:

The values of cover are in general close to the 25 mm limit as specified in the Portuguese code; however, the values are significantly lower at some spots of the zones surveyed;

In general, carbonation has progressed until very close to the reinforcement; however, at some spots of the zones surveyed, the carbonation process has extended to beyond the reinforcement;

The measured chloride content at the inside surface of the silos is 0.09% of cement mass at reinforcing depth (chart 2) , lower than the outside value and the critical limit value set in standard ENV 206 (1), i.e. 0.4% of the cement mass;

The rate of corrosion is very low in the zones tested ( 0.02 to 0.04 $\mu A/cm^2$) and is associated with high electric potential – 34 to –147 mV and values of the concrete resistivity of 120 Kohm.cm;

The zones surveyed did not present visible anomalies such as fissures, oxide stains, concrete spalling and visible corrosion of reinforcements, which usually show up in a later stage of concrete deterioration due to the reinforcement corrosion.

This being so, data obtained do not point to the existence of significant anomalies resulting from a process of deterioration of reinforcement due to corrosion in the inner surfaces. Nonetheless, in the zones of the reinforced concrete parts in which the thickness of cover is less than the depth of concrete carbonation rebars are likely to have lost passivation. The rate of deterioration progress (in the phase of propagation) corresponding to this process will essentially depend on the amount of water and oxygen in the concrete. As the bins are usually filled with grain, with very low moisture and very little oxygen available, corrosion is expected to proceed slowly.

## ORIGINAL DETERIORATION MODEL

On basis of the study reported it is possible to establish the deterioration model for the silo.

General corrosion of reinforcements is considered to be the main cause for the existing deterioration. The zones showing defective cover or poorer quality concrete or carbonation up to reinforcement or else high chloride content are potential zones of concrete deterioration.

On the external concrete surfaces of the silo, decay is due to reinforcement corrosion resulting from the combined action of depassivation due to carbonation and high chloride content in the concrete of the outer cover.

As on the inner face of the silo bins, both the chloride content and moisture are low, the risk of corrosion is low and is due to carbonation only.

## INTERVENTION STRATEGY AND REPAIR DESIGN OPTIONS

Several repair options were set out. The more drastic solution, taken as a yardstick for the cost-benefit analysis of the other solutions, consisted in the construction of a new silo – cost: US$4.0 million; completion time: 2 years.

Table 1. shows a comparison of the rehabilitation options available.

Constraints put by the Owner on the rehabilitation works can be summed up as follows:

- Financial limits– US$1.0 million
- Interruption in the use of silo bins – at maximum, two cells at a time for the total period of one year.

The option d) in table 1 was chosen, due to fit the financial limitations, and this Is expected to ensure a 25-year lifetime.

As the chosen option involves a patch work repair, it was sought to minimize negative effects for the non-repaired zones, and mainly for boundary zones by using topic migrating corrosion inhibitors, applied on the totality of the exposed surface of concrete, aiming at a general repassivation of steel reinforcement.

A basic requirement for a durable concrete rehabilitation is general surface coating with a paint previously tested and artificially aged, to confirm its appropriate resistance to the chloride ion penetration, diffusion of carbon dioxide, its being impervious to liquid water and permeable to water vapour. Such operation will possibly be the most important factor to ensure the required 25-year durability of the non repaired areas.

## THE REPAIR PROJECT

The rehabilitation operations developed during 1999 and consisted of repairing the anodic zones in the structure by restoring a mean thickness of 8 cm in the envelope using sprayed concrete, as well as the general spraying of migrating corrosion inhibitors of, and overall coating of the structure with an acrylic paint capable of resisting chloride penetration and carbon dioxide diffusion.

The repair process consisted, therefore, of the following steps:

a) Removal of deteriorated concrete by means of light pneumatic hammers (picture2) in order to expose the corroded reinforcements, care being taken so as to mark the contour of the repaired zones with a diamond disk in a way to avoid the presence of thin scales in the material sprayed at the boundaries.

b) Sandblasting of the exposed reinforcement in order to remove all corrosion products (picture 3).

c) Dry-mix shotcreting using double-chamber machines, assuring a concrete cover of 4 cm minimum (picture 4).

d) Spraying of the migrating corrosion inhibitor.

e) Application, on all external concrete surfaces, of a coat with dry total thickness of 150 micron using acrylic paint with organic solvent (picture 7).

Upon characterisation of the locally available materials, the following composition was selected for the sprayed concrete:

Cement, ASTM type I, class 42,5MPa: 375 kg/m3
Crushed basaltic aggregate (D=6mm): 1800 kg/m3
Silice fume: 15 kg/m3
Polypropylene fibres: 2 kg/m3
Migrating corrosion inhibitor MCI 2001: 3 kg/m3
W/C: 0.35 to 0.4

Fibers were used in order to minimize retraction cracking efects.

Concrete was applied by certified shotcreting operators in compliance with ACI standards.

A compressive concrete strength of 45Mpa was obtained as well as low permeability and porosity, and concrete bond to the original concrete exceeded the tensile strength of the original concrete (pull-off test), data in table 2.

## QUALITY ASSURANCE

The contractor had set up a quality assurance system in accordance with ISO 9002 standard, which was recently certified by a local accredited certification body.

In the frame of the company's quality assurance system, a quality plan was designed before and implemented during the silo repair work, including control of supplies and repair processes, inspection and testing in the course of the works and on the final product as well as accurate recording of all evidence on the controls carried out.

To control the repair process the following inspections and tests shown in table 2. were performed.

## MONITORING

The repair multiple strategy aiming at durability is going to be close monitored in the next years, by means of a corrosion monitoring system, involving a number of sensors embedded in the concrete. The general objective is to assess with sufficient accuracy the real durability of the repair works performed, and, in particular, to foresee the need for renovation of the protection coating. In this way, the time-to-corrosion can be determined continuously.
Both new repair concrete and old concrete, treated with corrosion inhibitors, are going to be monitored.
On the repaired surfaces, four areas of 1 m2 each are monitored (picture 6). Close to each monitored area a sensor was placed in the original non repaired concrete (top of picture 6).
The monitoring system consists of different types of embedded sensors, capable of measuring:

- Macrocell current
- Electrochemical potential of reinforcing steel
- Concrete electrical resistance
- Temperature.

Two different macrocell current sensors were built and installed.
On the original (non repaired) concrete the sensor consists of a core taken from another non repaired zone of the silo, containing a original reinforcement bar, instrumented in the laboratory, and reinstalled with cement mortar. The original bar is the anode and a stainless exterior grid the cathode of the cell. On the spayed concrete the embedded multi- macrocell consists on two steel anodes at two different depths and a stainless steel cathode.
Sensors for electrochemical resistance measurements in sprayed concrete consist on two graphite small rods separated and in two different depths to evaluate changes due to temperature, moisture, and chloride concentration.
Temperature sensors were also embedded on each monitoring area.
Data are acquired by means of a datalogger connected to the different probes.

References:

(1) ENV 206 - Concrete performances, production, placing and compliance criteria, 1998

Table 1. Comparison of rehabilitation options available.

| Rehabilitation option | Cost (million US$) | Delay (years) | Economical life time (years) |
|---|---|---|---|
| a) Total replacement of concrete on the external surface of the silo (6000 m2) | 2 | 2 | 50 |
| b) Repair of spalled zones (20% of total area), electrochemical desalinisation and re-alkalinisation, and total external painting | 1.5 | 2 | 50 |
| c) Exterior local repair (10% of total area) and cathodic protection system either through a sacrificial anode or impressed current | 2.5 | 2 | 50 |
| d) Repair of anodic zones (30% of total area), general application of migrating inhibitors of corrosion and total external protection through a protective coating against concrete carbonation and penetration of chlorides | 0.9 | 1 | 25 |

Table2. - Quality control inspection and testing

| Operation | Inspection & testing | Specification | Obtained values |
|---|---|---|---|
| Surface preparation | • Visual inspection<br>• Pull off tests | > 1 Mpa | 1,2 Mpa |
| Sprayed concrete | • Control of aggregate grain-size<br>• Control of concrete proportioning<br>• Control of application and cure<br>• Control of cover thickness<br>• Determination of compressive strength<br>• Determination of bond stress to original concrete (picture 5) | 4 cm<br>45 Mpa<br>> 1 Mpa | 4.2 cm<br>50 Mpa<br>1,2 Mpa |
| Corrosion Inhibitor: | • Dosage Rate | 3 $m^2$ / kg | 2,8 $m^2$/Kg |
| Painting: | • Laboratory control of paint characteristics and performance with a view to concrete protection<br>• Control of dry film thickness | 150 micron | 200 micron |

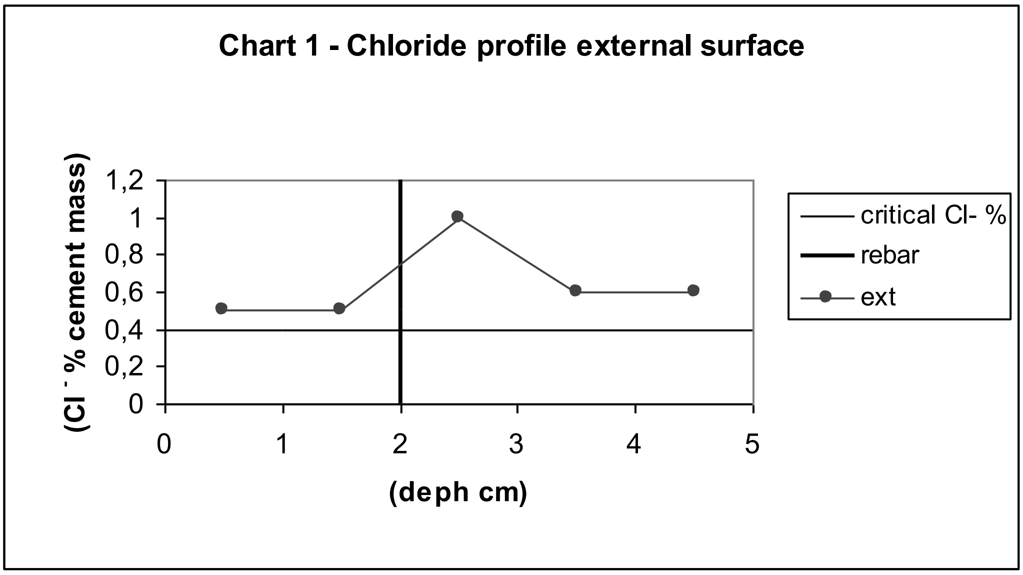
Chart 1 - Chloride profile external surface
(Cl⁻ % cement mass)
1,2
1
0,8
0,6
0,4
0,2
0
0
1
2
3
4
5
(deph cm)
critical Cl- %
rebar
ext

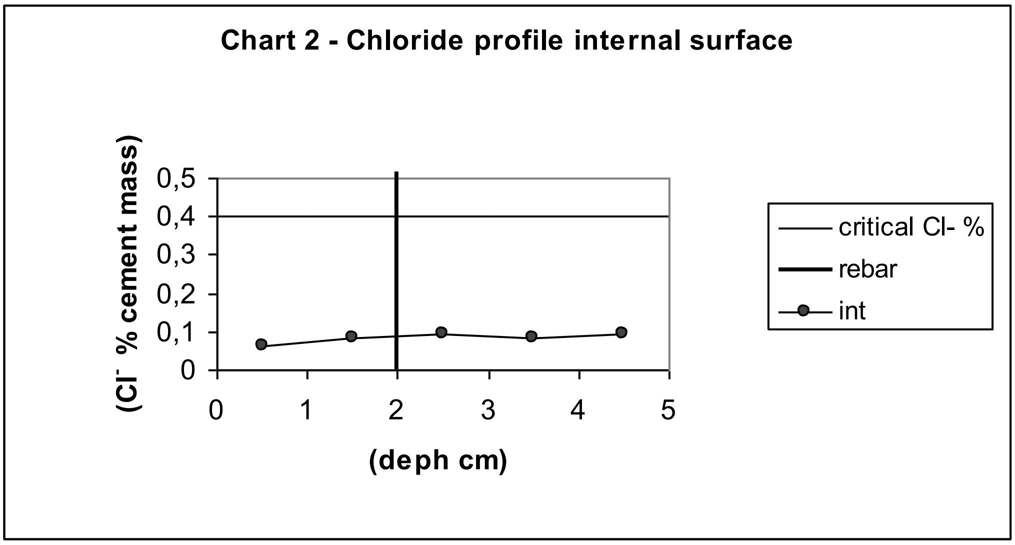


Chart 2 - Chloride profile internal surface

Pictures:

Picture1 - General silo aspect during rehabilitation, left – previous repair works, right actual repair works

Picture 2 – Removal of deteriorated concrete

Picture 3 – After sandblasting, ready to shotcrete

Picture 4 – Concrete spraying

Picture 5 - cores after pull - off test (rupture in original concrete)

Picture 6 - Monitoring system

Picture 7 – Final painting.