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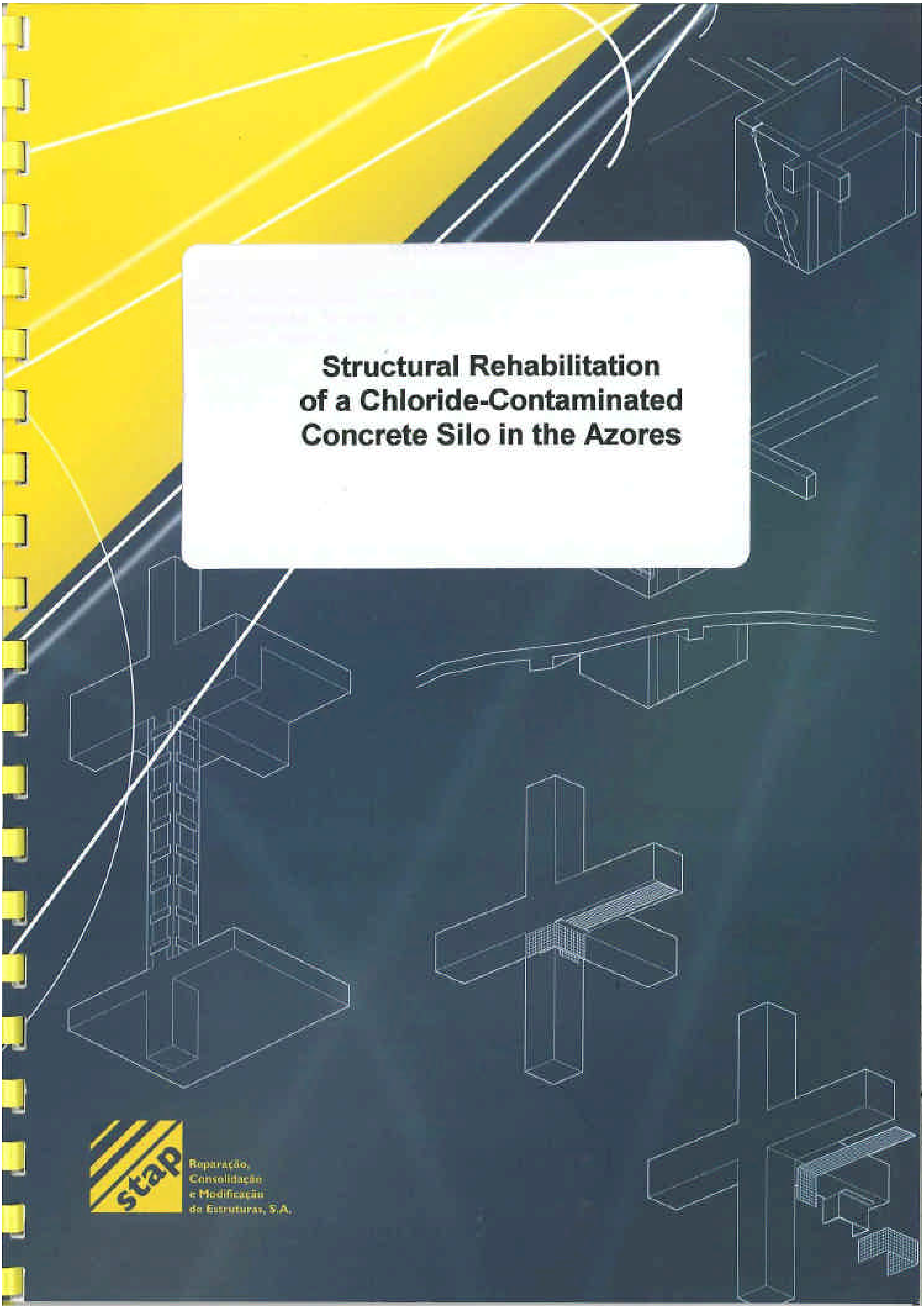
International Concrete Repair Institute

Structural Rehabilitation of a Chloride-Contaminated Concrete Silo in the Azores



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Structural Rehabilitation of a Chloride-Contaminated Concrete Silo in the Azores

INTRODUCTION

A reinforced concrete grain and food-stuff silo, built in 1980 in Lagoa, not far from Ponta Delgada, Azores, was subject to full structural rehabilitation just short of its 20th anniversary.

The structure, part of a feed-mill belonging to Sociedade Açoreana de Sabões, consists of a 62 m (203 ft) high equipment tower and a battery of 3x4 cylindrical bins, 6.5 m (21.3 ft) in diameter and 50 m (164 ft) high The exposed external surface amounts to 6000 m^2 (7200 sqyd) and no protective coating or painting was originally considered. The structure stands about 100m (110 yds) from sea, in a windy site, with periods of broad temperature cycles, almost permanently under sea spray conditions.

The silo was built by the slipform method, using very porous volcanic aggregates and beach sand. For already some years, signs of significant deterioration had been noticed, mainly widespread concrete spalling owing to corrosion of reinforcement (Figure 1).

Figure 1 – Area showing severe deterioration, marked for concrete removal.

CONDITION SURVEY AND ASSESSMENT

Faced with the low durability of successive piecemeal repairs, the Owner decided to order a thorough and accurate analysis of the anomalies in order to enable a full rehabilitation of the structure. A complete assessment program was established, involving tests both on site and in the laboratory, to characterize the structure and its materials, diagnose the deterioration process and detemine its extension.

The compressive strength of the concrete was found to vary greatly around an average of 25 MPa (3600 psi). The w/c was evaluated as ranging from 0.35 to 0.50 and porosity was high. Microcracking facilitated the penetration of aggressive agents as well as their mobility within the concrete mass.

On the **external surfaces,** the thickness of cover was found to vary significantly. The mean thickness values ranged from 16 to 35 mm (0.6 to 1.3 in).The depth of carbonation ranged from 10 to 65 mm (0.4 to 2.6 in), showing a marked heterogeneity of the concrete. 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 was high, 0.6% to 1% of cement mass at reinforcement depth (Figure 2), and showed that the high chloride content obtained on the external surfaces was mainly due to the diffusion of the air-borne chlorides.

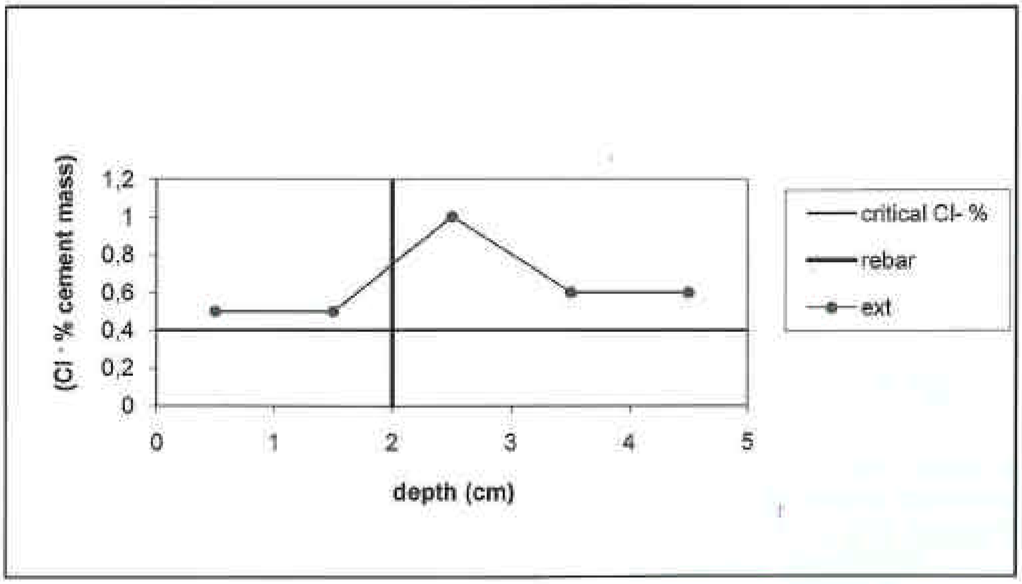

Fig. 2 – Measured chloride content near the external surface of the silo.

The results obtained through measurement of corrosion rate, electric potentials and concrete resistance showed that the risk of active corrosion was widespread.

On the **internal concrete surfaces**, the values of cover were in general close to 25 mm (1 in). However, the values were significantly lower at some spots of the zones surveyed.

In general, carbonation had progressed until very close to the reinforcement and extende beyond, at some spots.

The measured chloride content at the inside surface of the silos was 0.09% of cement mass at reinforcing depth (Figure 3), lower than the outside value and lower tha the critical limit value of 0.4% of the cement mass.

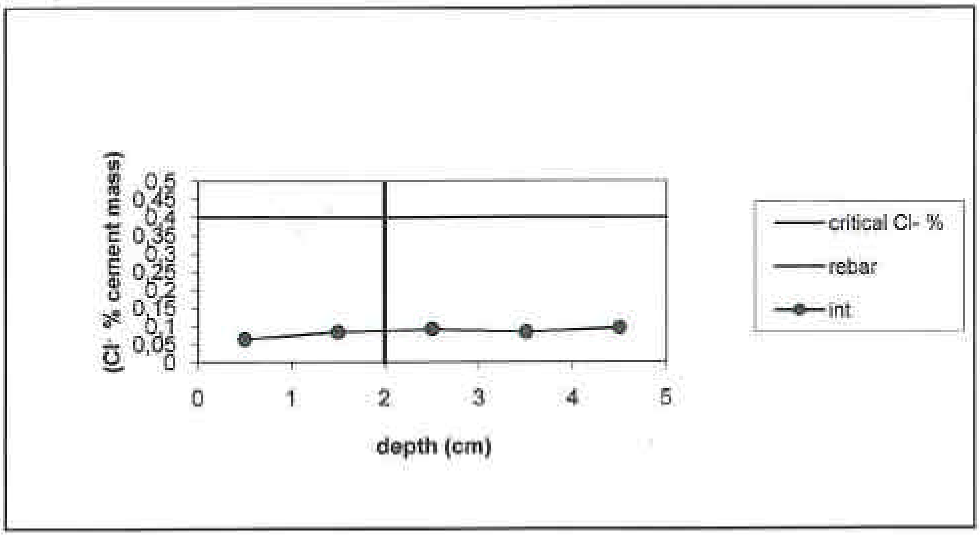

Fig. 3 - Measured chloride content near the internal surface of the silo.

The results obtained through measurement of corrosion rate, electric potentials and concrete resistance did not point to the existence of significant reinforcement corrosion in the inner surfaces, which, additionally, did not show the usually related anomalies.

INTERVENTION STRATEGY AND REPAIR DESIGN OPTIONS

Several repair options were envisaged. The more drastic solution, taken as a measuring stick for the cost-benefit analysis of the other solutions, consisted in the construction of a new silo, at a cost of US$4.0 million[1] and a completion time of 2 years. Table 1. shows a comparison of the four rehabilitation options available.

Table 1. Comparison of rehabilitation options available.

[1] Based on the approximate 1998 rate of 1 US Dolar = 172 Portuguese Escudos.

Rehabilitation option	Cost (million US$)	Constr. time (years)	Expected life (years)
a) Total replacement of concrete on the external surface of the silo (6000 m^2)	2	2	50
b) Repair of spalled zones (20% of total area), electrochemical desalination and re-alkalination, 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 corrosion inhibitors and overall external protection through a protective coating against concrete carbonation and penetration of chlorides	0.9	1	25

Due to budget considerations and operational constraints put forward at the time by the Owner, option d) was chosen.

THE REPAIR PROJECT

The rehabilitation operations took place during 1999 and consisted of the following steps:

a) Removal of deteriorated concrete by means of light pneumatic hammers (Figure 4), care being taken to avoid formation of thin scales at the repairs' boundaries during the ensuing spraying of repair concrete.

b) Cleaning of the exposed reinforcement in order to remove all corrosion products (Figure 5).

c) Dry-mix shotcreting using double-chamber machines, assuring a concrete cover of 4 cm (1,6 in) minimum (Figure 6).

d) Spraying of the migrating corrosion inhibitor.

e) Application, on all external concrete surfaces, of a coat with dry total thickness of 150 micron (6 mils) using acrylic paint.

The following composition was selected for the sprayed concrete:

Cement, ASTM type I, class 42.5MPa (6100 psi): 375 kg/m^3 (23 pcf)
Crushed basaltic aggregate (D=6mm): 1800 kg/m^3 (112 pcf)
Silica fume: 15 kg/m^3 (0.9 pcf)
Polypropylene fibres: 2 kg/m^3 (0.12 pcf)

Migrating corrosion inhibitor: 3 kg/m^3 (0.16 pcf)
W/C: 0.35 to 0.4.

Figure 4 – Removal of deteriorated concrete.

Figure 5 – Concrete surface after preparation, ready for concrete spraying.

Figure 6 – Concrete spraying.

Figure 7 – Small diameter cores after pull-off test (failure through old concrete).

QUALITY ASSURANCE

A quality plan was implemented during the silo repair work, including control of supplies and repair processes, inspection and testing over the course of the works and on the final product (Figure 7), as well as accurate recording of relevant evidence on the controls carried out.

To control the repair process the inspections and tests shown in table 2. were carried out.

Table2. - Quality control inspection and testing

Operation	Inspection & testing	Specification	Obtained values
Surface preparation	• Visual inspection • Pull off tests	> 1 MPa (145 psi)	1.2 MPa (174 psi)
Sprayed concrete	• Control of aggregate grain-size • Control of concrete proportioning • Control of application and cure • Control of cover thickness • Determination of compressive strength • Determination of bond stress to original concrete	4 cm (1.6 in) 45 MPa (6530 psi) > 1 MPa (145 psi)	4.2 cm (1.7 in) 50 MPa (7250 psi) 1.2 MPa (174 psi)
Corrosion Inhibitor:	• Dosage	3 m^2 / kg (14.6 sqft/lb)	2.8 m^2/kg (13.7 sqft/lb)
Painting:	• Laboratory control of paint characteristics and performance in view of concrete protection • Control of dry film thickness	150 micron (6 mils)	200 micron (7.9 mils)

MONITORING

A corrosion monitoring system was installed, involving a number of sensors embedded in the silo walls, both in new and old concrete. The general objective was to assess, with sufficient accuracy, the real durability of the rehabilitation job, and, in particular, to foresee the need for renovation of the protection coating.

On the repaired surfaces, four areas of 1 m^2 (10.8 sqft) each were choosen (Figure 8a). Close to each monitored area a sensor was placed in the original non repaired concrete (top of Figure 8a).
The monitoring system installed consists 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 in the original (non repaired) concrete and in the spayed concrete. Sensors for electrochemical resistance and temperature measurements were also emdedded in the sprayed concrete in each monitoring area. All acquired data are channeled to a central datalogger (Figure 8b).

a b

Figure 8 - Monitoring system: a – Sensors to be embedded in the new concrete and inserted in the existing concrete (top); b – Data logging central.

Table 3 presents the results of macrocell current, potential, concrete resistance and temperature from all sensors, obtained at the first months of monitoring. Figures 9 to 12 show examples the data obtained, from June 2002 in two of the sensors installed, representing the two rehabilitation approaches (sensors 1 and 2). Figures 9 to 11 present the measurements of the macrocell corrosion current, the electrical potential and the concrete resistance, obtained in sensor 1 installed in a repaired area (see Table 3). Figure 12 presents the macrocell corrosion current measured in sensor 2, installed in a non repaired area.

Table 3 - Results obtained, in all sensors, immediately after installation and two months after.

Corrosion sensor location	Type of repair	Parameter	Date	
			3/23/00	4/2/00
Sensor 1 10 m from top, bin 4	Repaired Coated	Corrosion Current (nA)	50	33
		Potential (mV, Mn/MnO_2)	-294	-289
		Electrical Resistance (kOhm)	38	11
Sensor 2 10 m from top, bin 4	Not repaired Coated	Corrosion Current (nA)	22	47
Sensor 3 25 m from top, bin 4	Repaired Coated	Corrosion Current (nA)	4	32
		Potential (mV, Mn/MnO_2)	-377	-373
		Electrical Resistance (kOhm)	47	19
Sensor 4 25 m from top, bin 4	Not repaired Coated	Corrosion Current (nA)	3662	2649
Sensor 5 10 m from top, bin 19	Repaired Coated	Corrosion Current (nA)	22	23
		Potential (mV, Mn/MnO_2)	-328	-315
		Electrical Resistance (kOhm)	50	
Sensor 6 10 m from top, bin 19	Not repaired Coated	Corrosion Current (nA)	789	264
Sensor 7 26 m from top, bin 19	Repaired Coated	Corrosion Current (nA)	0	22
		Potential (mV, Mn/MnO_2)	-343	-333
		Electrical Resistance (kOhm)	51	9
Sensor 8 26 m from top, bin 19	Not repaired Coated	Corrosion Current (nA)	14	23

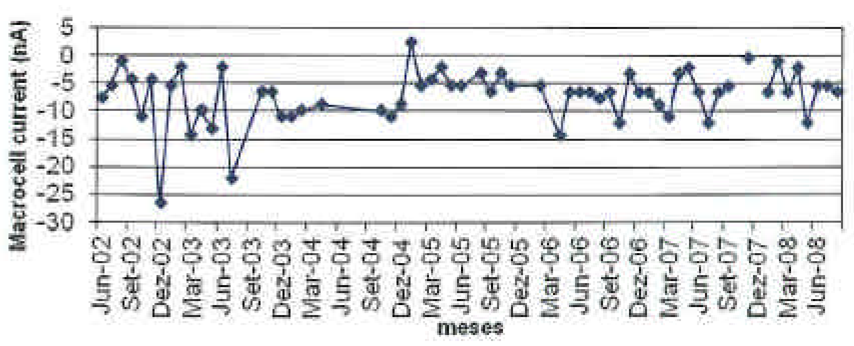

Figure 9 – Macrocell current at sensor 1 (repaired area).

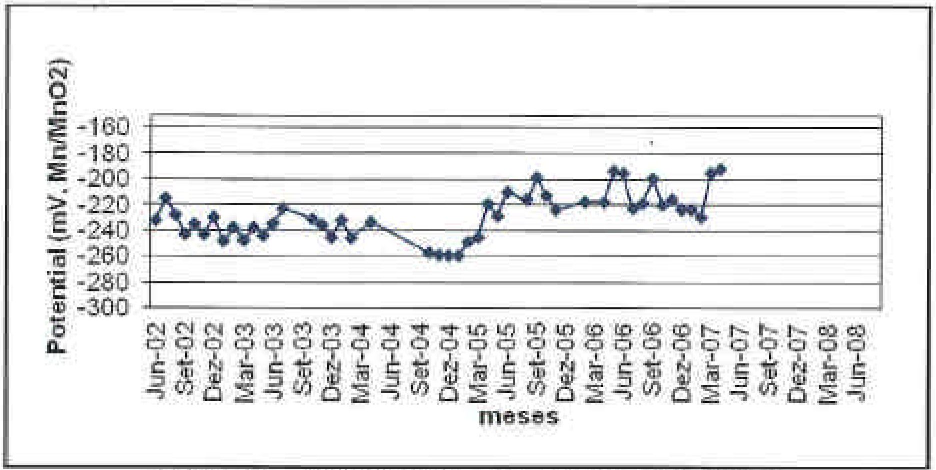

Figure 10 – Potential at sensor 1 (repaired area).

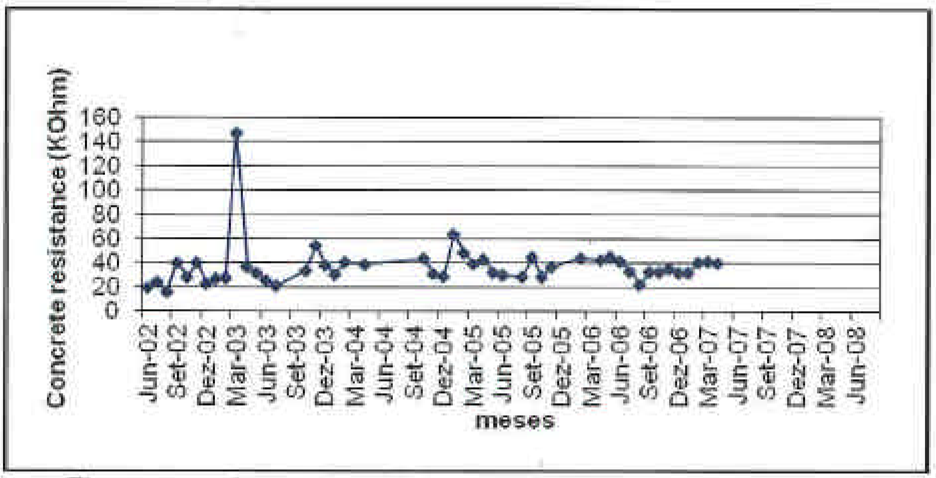

Figure 11 – Concrete resistance at sensor 1 (repaired area).

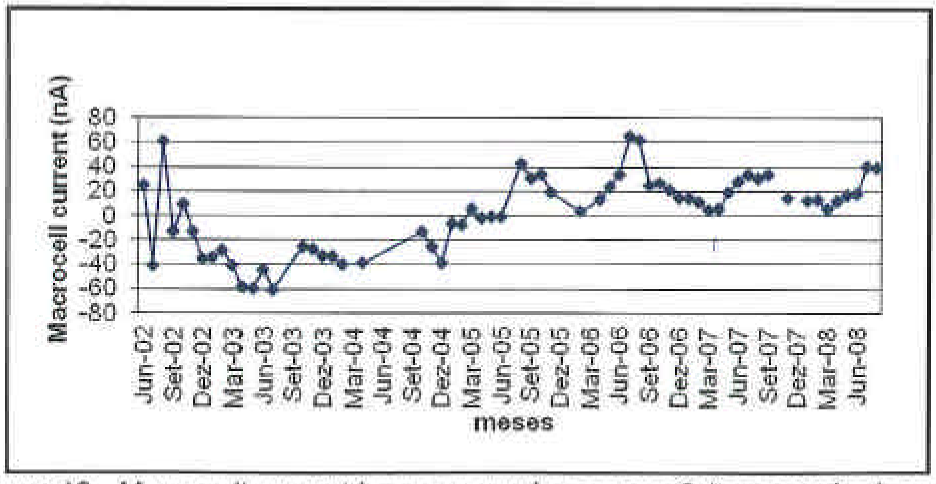

Figure 12 - Macrocell current in one corrosion sensor 2 (non repaired area).

The values of the potential obtained in the repaired areas were initially very negative. However, after two years they were shifting to less negative values, a trend compatible with the repassivation of the rebars. In these areas, the macrocell current values obtained during the eight years up to 2008 have been very low, indicating low corrosion activity. The agreement between the values of the macrocell current with the values of the potential measurements, indicates that the reinforcing steel has been maintained in the passive state and therefore free of corrosion. This demonstrates de effectiveness of the repair method, for the monitoring period.

In the areas where the concrete was not replaced, the values of macrocell current obtained initially were also high, indicating some corrosion activity. Again, the values decreased with time to levels of the same order of magnitude of those measured in the repaired areas. This indicates a reduction of the corrosion activity and its absence since the rehabilitation works, in spite of the concrete still being contaminated with chlorides.

The concrete electrical resistance values show generally a pattern compatible with the seasonal variation of temperature and rain fall. No trend towards lower values was observed over time.

CONCLUSION

The rehabilitation of the Lagoa silo (Figure 13) presented various challenges: design and construction deficiencies, budget limitations, operational constraints and adverse jobsite environment. The success of the intervention is to be credited to the excellent partnership developed between Owner, Designer and Contractor. This enabled a strict compliance with the appropriate methodology of structural concrete rehabilitation throughout the intervention and beyond. The projet is now nearing the term of its ten year warranty. However, monitoring will continue to enable timely maintenance and to make sure that the silo goes on fulfilling its role in satisfactory safety and operational conditions.

Figure 13 – Recent view of the rehabilitated Lagoa silo.