Structural Rehabilitation of a Chloride-Contaminated Concrete Silo

Lagoa, the Azore Islands

Submitted by STAP, SA

A reinforced concrete grain and foodstuff silo, built in 1980 in Lagoa, not far from Ponta Delgada, Azores, was subject to full structural rehabilitation. The structure consists of a 203 ft (62 m) high equipment tower and a battery of 3 x 4 cylindrical bins, 21.3 ft (6.5 m) in diameter and 164 ft (50 m) high. The exposed external surface, 7200 yd^2 (6000 m^2), had no protective coating or painting. The structure stands about 110 yds (100 m) from the 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 some years, there were signs of significant deterioration—mainly widespread concrete spalling due to corrosion of reinforcement (Fig. 1).

CONDITION SURVEY AND ASSESSMENT

Faced with the low durability of successive piecemeal repairs, the owner ordered a thorough analysis of the structure. The assessment involved tests both on site and in the laboratory to characterize the structure and its materials, diagnose the deterioration process, and determine the extent of the problem.

The compressive strength of the concrete varied greatly, around an average of 3600 psi (25 MPa). The water-cement ratio (*w/c*) ranged from 0.35 to 0.50 and porosity was high. Microcracking facilitated the penetration of aggressive agents and their mobility within the concrete mass.

On the external surfaces, the concrete cover thickness of cover varied significantly. The mean thickness values ranged from 0.6 to 1.3 in. (16 to 35 mm).The depth of carbonation ranged from 0.4 to 2.6 in. (10 to 65 mm). In 75% of the cases where reinforcing was exposed, the carbonation depth was found to equal or exceed the thickness of the cover.

Chloride content was also high—0.6 to 1% of cement mass at reinforcement depth—and showed that the high chloride content on the external surfaces was mainly due to the diffusion of the airborne chlorides.

Fig. 1: Area showing severe deterioration, marked for concrete removal

Measurement of corrosion rate, electric potentials, and concrete resistivity showed that the risk of active corrosion was widespread.

On the internal concrete surfaces, the concrete cover was, in general, close to 1 in. (25 mm). However, it was significantly lower at some spots of the zones surveyed. In general, carbonation had progressed until very close to the reinforcement and extended beyond, at some spots.

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

The results obtained through measurement of corrosion rate, electric potentials, and concrete resistivity did not point to the existence of significant reinforcement corrosion in the inner surfaces.

INTERVENTION STRATEGY AND REPAIR DESIGN OPTIONS

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

Due to budget considerations and operational constraints of 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 using light pneumatic hammers (Fig. 2), with 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 to remove all corrosion products;
c) Dry-mix shotcreting using double-chamber machines, assuring a concrete cover of 1.6 in. (40 mm) minimum (Fig. 3);
d) Spraying of the migrating corrosion inhibitor; and
e) Application of acrylic paint on all external concrete surfaces, of a coat with dry total thickness of 6 mils (150 micron).

[1]*Based on the approximate 1998 rate of 1 U.S. Dollar = 172 Portuguese Escudos.*

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, as well as accurate recording of control readings.

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 the real durability of the

TABLE 1: COMPARISON OF REHABILITATION OPTIONS AVAILABLE

Rehabilitation option	Cost, (million U.S.$)	Construction time, years	Expected life, years
A. Total replacement of concrete on external surface of silo (64,583 ft^2 [6000 m^2])	2	2	50
B. Repair of spalled zones (20% of total area), electrochemical desalination and realkalization, and total external painting	1.5	2	50
C. Exterior local repair (10% of total area) and cathodic protection system either through 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 protective coating against concrete carbonation and penetration of chlorides	0.9	1	25

Fig. 2: Removal of deteriorated concrete

Fig. 3: Concrete spraying

rehabilitation job and, in particular, to foresee the need for renovation of the protection coating.

On the repaired surfaces, four areas of 10.8 ft^2 (1 m^2) each were chosen (Fig. 4). Close to each monitored area, a sensor was placed in the original nonrepaired concrete (top of Fig. 4).

The monitoring system installed consists of embedded sensors capable of measuring:

- Macrocell current;
- Electrochemical potential of reinforcing steel;
- Concrete electrical resistivity; and
- Temperature.

Two different macrocell current sensors were built and installed in the original (nonrepaired) concrete and in the sprayed concrete. Sensors for electrochemical resistivity and temperature measurements were also embedded in the sprayed concrete.

The values of the potential in the repaired areas were initially very negative. After 2 years, however, they were shifting to less negative values, a trend compatible with the repassivation of the reinforcing steel. In these areas, the macrocell current values obtained during the 8 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 is, therefore, free of corrosion. This demonstrates the effectiveness of the repair method for the monitoring period.

In the areas where the concrete was not replaced, the values of the macrocell current initially obtained 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 because the rehabilitation works, in spite of the concrete still being contaminated with chlorides.

The concrete electrical resistivity values show a pattern compatible with the seasonal variation of temperature and rainfall. No trend toward lower values was observed over time.

LONGEVITY OF REPAIR SOLUTION

The rehabilitation of the Lagoa Silo (Fig. 5) presented various challenges: design and construction deficiencies, budget limitations, operational constraints, and an adverse job site environment. The project success can be credited to the excellent partnership developed between owner, designer, and contractor, enabling a strict compliance with the appropriate methodology of structural concrete rehabilitation throughout the intervention and beyond. The project is now nearing the term of its 10-year warranty. 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.

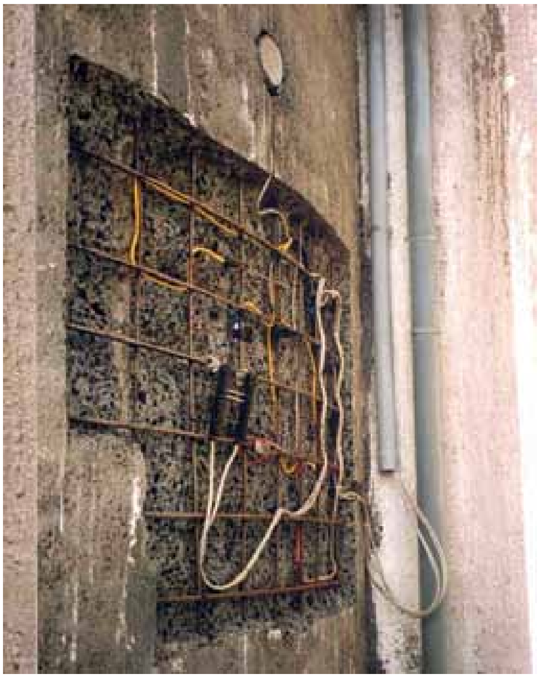

Fig. 4: Monitoring system—sensors to be embedded in the new concrete and inserted in the existing concrete (top)

Fig. 5: Recent view of the rehabilitated Lagoa Silo

Lagoa Concrete Silo

OWNER
Soc. Acoreana DeSaboes, SA

PROJECT ENGINEER/DESIGNER
GRID
Portugal

REPAIR CONTRACTOR
STAP, SA
Lisbon, Portugal

MATERIAL SUPPLIER/MANUFACTURER
Technochem Italiana, S.p.A.
Barzana, Bergamo, Italy