Evaluation and Repair of a Liquid Sulphur Holding Tank

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Reinforced concrete structures have been in use for many years in different applications. These structures can take a variety of shapes and sizes and can be designed to support many types of load conditions. In most cases, these structures can perform well for decades with relatively little or no maintenance. In industrial facilities, however, these structures are subjected to a variety of adverse conditions. Exposure to the elements, thermal changes, and acid attacks are not uncommon. The structures in these facilities must accommodate these various exposures.

Reinforced concrete tanks are used in many gas plants to contain liquid sulphur. These tanks are usually buried so that the roof and only a small portion of the walls are exposed. The size and structural framing of these tanks can vary.

The sulphur temperatures can range between 120 and 200 °C, resulting in significant thermal stresses in the structure. The tanks are drained and filled daily, causing a cyclical change in load and temperature. Also, the sulphur vapor can combine with moisture to create a sulphuric or a sulphurous acid. This combination of high acidity and high temperature results in an extremely aggressive and corrosive environment. Coatings inside the tank are typically not used, as they cannot withstand the combined effects of high temperature, acid attack, and erosion while still maintaining flexibility to bridge small cracks that can form in the concrete. Subsequently, the concrete is subjected to attack, which can lead to deterioration of the structure.

The following case study presents the results of Read Jones Christoffersen Ltd.'s evaluations and repairs of a particular sulphur tank located in a gas plant in central Alberta. The tank was constructed in 1978 and we have been monitoring the condition of the structure since 1993. We undertook repairs in 1993 and are presenting our findings with respect to the ongoing deterioration of the structure and the performance of the repairs.

Evaluation of the Structure

To assess the condition of the tank, a thorough evaluation was performed. The evaluation determined the tank's structural condition, the need for repair or maintenance, and provided an indication as to the safety and expected remaining service life of the structure. The testing consisted of:

- A visual inspection of the exterior exposed elements to determine if there were any obvious signs of distress, deflection, or deterioration in the structure;
- A thorough inspection of the interior of the tank to determine the condition of the structure. This is essential as we found that the tanks can appear to be in very good condition on the outside but could be suffering extreme structural distress on the inside. This was particularly evident on the underside of the roof structure and the interior surfaces of the upper portion of the walls where exposure to acid attack is greatest;
- Chain drag testing of the roof surface and hammer sounding of vertical and soffit areas on the interior to locate where concrete delamination had occurred;
- Selective concrete removal to examine the condition of the underlying reinforcing steel;
- Materials testing to determine concrete compressive strength, air entrainment, cement type, and depth of sulphur penetration in the concrete;
- Drawing review to obtain pertinent information on the structure such as specified concrete cover, reinforcing details, cement type, and design criteria to determine critical areas of reinforcement and how the structure was intended to perform; and
- A design review to determine whether the existing level of deterioration has reduced the load-carrying capacity to where safety is compromised and to establish possible causes for any observed excessive deflection or cracking.

Description and History of Structure

The sulphur tank in this study was constructed in 1978 and is 50 m (164 ft) long, 19 m (62 ft) wide, and 4.6 m (15 ft) deep. The lower 3.6 m (11.8 ft) of the tank is buried, with only the roof and 1 m (3.3 ft) of wall structure exposed. The structure is supported on a large 450 mm (1.5 ft) thick concrete pad, which acts as the floor slab and foundation. The roof is a 300 mm (1 ft) flat slab with 150 mm (6 in.) drop panels supported on

450 mm (1.5 ft) foundation walls and two interior rows of concrete columns spaced at approximately 6500 mm (21 ft) centers. In 1982, an explosion in the tank required replacement of the roof and upper portion of the walls.

Concrete deterioration was evident during a 1988 internal inspection. A sprayed concrete (shotcrete) was applied by the owners at that time to repair these areas. The next internal inspection was performed in 1990 and it was noted that these repairs had failed. Shotcrete repairs were again performed under the direction of the owners in 1990.

In the spring of 1993, this writer performed an evaluation of the tank. At that time, the exterior structure displayed some cracking; however, it generally appeared to be in good condition. Chain drag testing of the roof did not reveal any significant deterioration.

An internal inspection of the tank uncovered considerable corrosion and concrete spalling of the upper portions of the wall and areas on the underside of the roof slab (Fig. 1). This corresponded with the region within the vapor space, where sulphur vapors and moisture combine to form a highly acidic environment. Approximately 10% of the roof slab and 40% of the wall surfaces had signs of deterioration. The shotcrete repairs performed in 1990 had totally failed. The condition of the exposed reinforcing bars was variable. In some areas, the reinforcing bars were corroded through the entire cross section, while in other areas, the exposed reinforcing bars were in excellent condition, with no loss of cross section.

Figure 1: Exposed and corroded reinforcing steel in upper portion of wall

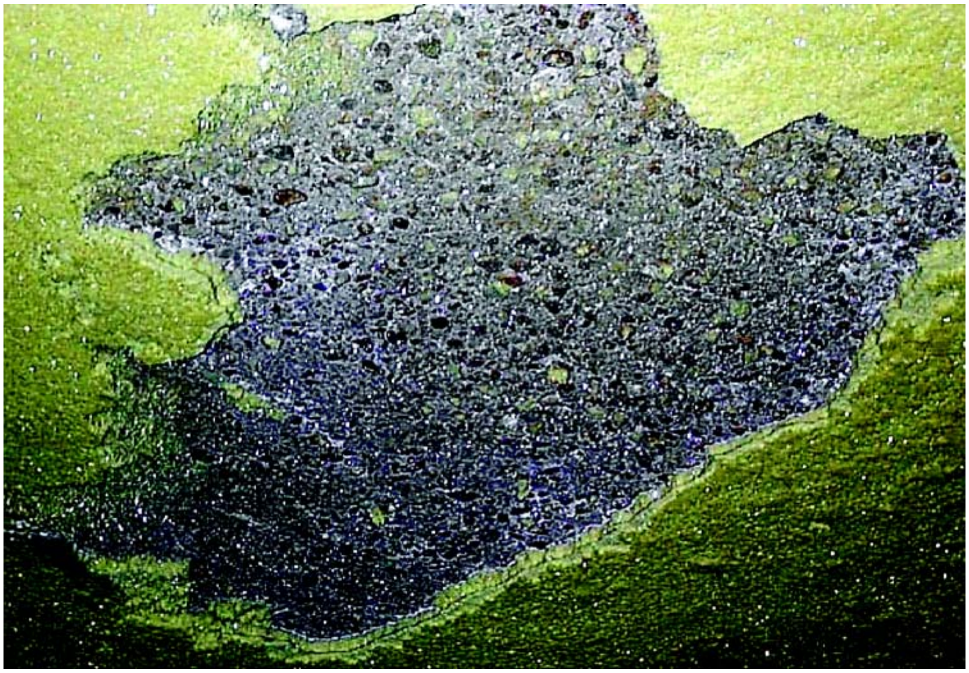

Figure 2: Exposed aggregate at underside of roof

Selective removal of the concrete around the protected reinforcing bars determined that the concrete cover varied from 20 to 40 mm (0.8 to 1.6 in.) and that the bars were typically in good condition.

There was a loss of cement paste and exposed aggregate in the underside of the roof and portions of the wall (Fig. 2). This was relatively uniform and we did not observe any exposed reinforcing steel in these areas.

Based on the deterioration evident, it was apparent that portions of the structure were unsafe, particularly at the roof slab where there was concern for its ability to support the significant piping and equipment situated on the tank. It was necessary to develop a repair program that would:

- Restore the load-carrying capacity of the structure to a safe condition;
- Perform in a very aggressive environment for a minimum specified period of time;
- Meet the owner's budget requirements; and
- Meet the owner's time constraints.

Repair Methods and Materials

It is our experience that the level of deterioration evident in reinforced concrete structures is greatly affected by the quality of concrete used during construction. Highly durable concrete, although not immune to damage, was generally found to perform better and last longer than structures where the concrete was highly permeable or of poor quality.[1] Poor workmanship such as improper consolidation or insufficient concrete cover can also result in premature deterioration.

In this project, the repairs previously completed for the owners had failed after a short time. These repairs consisted of a spray-applied concrete and vertical patch materials placed over the damaged areas. In some cases, mechanical fasteners and welded wire mesh were placed in the patch to anchor the repair materials to the base concrete. These areas failed due to:

- Inadequate surface preparation, resulting in debonding of the repair materials;
- Improper consolidation and/or poor workmanship;
- Improper selection of repair materials and procedures;
- Corrosion of the reinforcing steel beneath the repair materials; and
- Lack of understanding regarding the behavior of the structure under applied loads and thermal stress.

The 1993 repair program consisted of partial and total replacement of the concrete members where structural damage was noted. Areas of exposed aggregate were not repaired during this program, as the deterioration evident had not affected the load-carrying capacity of the structure.

In the partial repair areas, the concrete was removed beyond the inner layer of reinforcing steel and to a sound concrete substrate (Fig. 3). The existing, exposed steel was replaced with new steel where possible. The remaining reinforcing steel was sandblasted clean of any cement and corrosion product. The exposed concrete surfaces in the repair area were thoroughly cleaned of loose materials and contaminants to provide a suitable surface for bond with the new repair materials.

Consideration was given to using high-alumina cement as a repair material. High-alumina cement has been used in the construction of similar tanks although this material can be costly, relative to a regular portland cement mixture. During the planning stages of the repair program, a cost-benefit analysis was performed based on the owner's requirement for an expected 15 to 20 year life for the structure. On this basis, it was decided to repair the structure using a highly durable, low permeability concrete.[2] The concrete mixture design had the following properties:

- Type 50 sulphate resistant cement;
- Low water-cement ratio of 0.40 (maximum);
- 8% silica fume;
- Air entrainment;
- 20 mm (0.8 in.) maximum aggregate size;
- Low slump (50 mm [2 in.] maximum); and
- Minimum 28-day compressive strength of 35 MPa (5000 psi).

To increase the protection to the reinforcing steel, a minimum concrete cover of 75 mm (3 in.) was provided in the repair areas.

Lined formwork was used to provide a smooth interior surface and to improve the durability of the repairs. Chairing the steel to the interior surface was not permitted to maintain the smooth concrete surface and to prevent any exposed steel from occurring on the interior surface where exposure to the liquid sulphur and vapors could occur.

Proper curing of the repair materials improves the performance of the concrete. Extended curing periods were not possible due to time constraints on the plant shutdown; therefore, curing periods varied from 7 days for the vertical repairs to 14 days for the areas of slab replacement.

The total repair cost for the project was approximately $400,000 (in 1993 Canadian dollars).

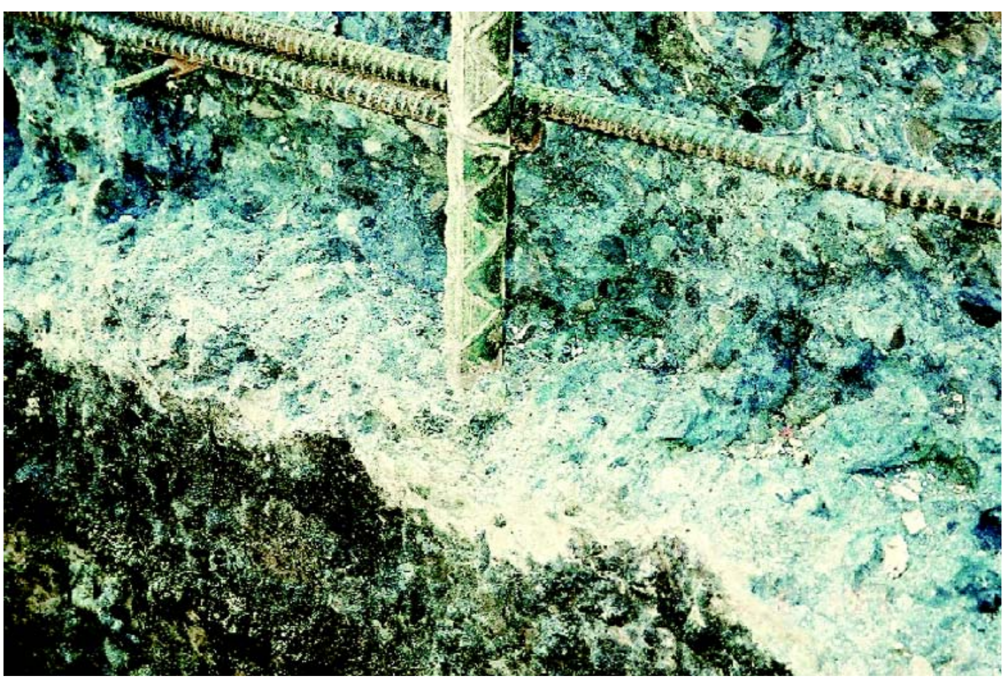

Figure 3: Patch preparation showing extent of concrete removal

Performance of Repairs

Figure 4: Area of repair in excellent condition after seven years of service

The repairs performed in 1993 were examined in 1996 and 2000 during plant shutdowns. After 7 years of service, the repairs have performed exceptionally well. We have noted the following:

- The original concrete is continuing to show signs of deterioration and loss of cement paste. Exposed aggregate was noted in many areas. Portions of the existing drop panels were also spalled from the underside of the roof slab;
- In the repair areas, the concrete surface was in excellent condition with only localized areas where minimal loss of surface paste was observed (Fig. 4);
- Some fine cracks were noted in the repair areas. These appeared to be due to restrained shrinkage and thermal stress in the structure. The repair areas were sound and performing as intended;
- Some loss of surface paste was noted in localized areas of the underside of the roof slab, adjacent to steam injectors. It was determined that pressurized steam injected into the tank would deflect off the surface of the sulphur and abrade the concrete in the vicinity of the injectors. These injectors were installed after the 1993 repair program and the damage was noted in 1996. The lines were relocated in 1996, and during our 2000 inspection, there did not appear to be further deterioration in these areas; and
- Approximately six small areas of debonded concrete (less than 0.1 m^2 [1 ft^2] in area) were detected in the repair areas in 1996. These were at the edges of repairs and may have been due to shrinkage of the patches or from impact at the time the formwork was removed. There were no noticeable changes in these areas during our 2000 inspection.

Satisfied Owner

Good performance of reinforced concrete structures exposed to aggressive environments can be achieved with the use of highly durable, low permeability concretes and by paying careful attention to details. Consideration must be given to:

- The use of good quality concrete;
- Attention to construction details;
- Increased concrete cover;
- Design and detailing of the reinforcing steel to minimize cracking; and
- Proper concrete curing.

Read Jones Christoffersen Ltd. has applied these methods to a number of other sulphur tanks with similar results. This case study indicates that under extremely aggressive environments, proper use of concrete can result in a repair that is durable and economical. In this case, the repairs are expected to meet or exceed the owner's expectations for performance.

References

1. ACI Committee 222, "Corrosion of Metals in Concrete (ACI 222R-89)," American Concrete Institute, Farmington Hills, Mich., 1989, 30 pp.

2. CSA Committee S413, CAN/CSA-S413-94, "Parking Structures—Structures Design," Canadian Standards Association, Ontario, Canada, 1994, 103 pp.

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