Cracking and Leakage at Reinforced Concrete Pomona Water Reservoir 5C
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Water Reservoir 5C

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Executive Summary

The concrete walls of the Pomona Water Reservoir 5C suffers from visible concrete cracking resulting in serviceability concerns, including leakage, corrosion of reinforcement, and eventually stability of the structure. The problem exists in all the walls around the perimeter of the tank. The cracks appear similar in nature as indicated by their predominantly vertical path, widest near the ground level and closing towards the top of the wall, and repetitive spacing. Dr. Piotr Moncarz, P.E., of Exponent inspected the exterior of the concrete tank on November 17, 2006, and on December 5, 2006, concrete core samples were removed from the walls for laboratory analysis. The source of cracking was identified to be shrinkage and temperature related. While the amount of dimensional change of the concrete depends on material properties of the concrete (this including construction practices), the distribution and width of resulting cracks is strongly dependent on the amount and location of the steel reinforcement placed in the wall. The cracking viewed during the inspection constitutes a repetitive repair item over the life of the structure. Unless moisture is prevented from free flow through those cracks, a progressive deterioration of the reinforcement and of structural integrity of the tank should be expected.
Introduction

Exponent Failure Analysis was retained by the City of Pomona, California to investigate the cause of cracking of the reinforced concrete tank structure of the Pomona’s Reservoir 5C, in Pomona, California. Many of the cracks present in the exterior wall of the tank are wide enough, and apparently penetrate through the thickness of the wall to result in water leakage from the tank to the exterior as already visible on an inspection of the tank. Prior attempts to seal some of the cracks show only limited success as leakage through cracks evidently sealed before has been observed. Exponent’s scope of work consisted of the followings:

- A site visit by Dr. Piotr Moncarz, P.E., on November 17, 2006.
- Removal of concrete core samples from the concrete walls on December 5, 2006.
- Petrographic analysis of a concrete core sample.
- Review of design documents, contract documents and specifications.
- Review of applicable codes and standards.
- Engineering analysis.

The subject reservoir was designed and constructed during the 2002 - 2003 period. The reinforced concrete rectangular concrete tank is 305-ft long by 207-ft wide and about 27-ft high (see Figure 1). The exterior walls are 3-ft thick and reinforced on vertical and horizontal directions (see Figure 2). Spacing of construction joints ranges from 17-ft to 38-ft (on all exterior walls).

The project specifications outline the concrete mix requirements for the exterior walls in detail as follows:

- 28-day compressive strength: 3500 psi
- Water-to-cement ratio: 0.45-by weight
- Slump: 4-inches maximum
- Maximum aggregate size: 1 ½-inch

The cast-in-place concrete walls were required to be water-cured for a minimum of five days. The walls were allowed to be cured using q water spray method or wet-burlap-method. Slabs and floors were required to be cured using a curing blanket method. Special curing requirements were made for high temperature low humidity days.
Figure 1. Plan of the Pomona Reservoir 5C
Figure 2. Typical cross-section of the exterior wall

- wall 3'-0" x 23' T x H
- foundation 19'-8" x 3'-3" B x H
- reinforcement #7 @ 12' each side
Concrete Cracking

During the November 2006 inspection, about two years after the construction of the reservoir, widespread concrete cracking on all exterior walls was observed (see Figure 3). The cracks are mostly vertical and few continue all along the height of the tank. The cracks are generally about up to 1/32-inch to 1/16-inch wide, enough to allow water to seep through the wall, and indeed, as seen in Figure 4, many cracks exhibit evidence of leakage. Not all cracks are believed to be through thickness. However, in absence of access to the inside of the tank, one cannot determine which cracks are through thickness and which are not.

Figure 3. Cracks on the exterior concrete walls
Figure 4. Leakage through cracks
Analysis

Concrete Coring and Petrographic Analysis

Four concrete cores were removed from the affected walls on December 5, 2006. The cores were 4-inch in diameter (nominal) and about 10-inch long. The core condition was visually inspected and recorded. The visual inspection of the cores showed the core concrete being similar in mix and placement. Petrographic analysis\(^1\) of one representative core\(^2\) was performed. Followings are the key observations made regarding the physical properties of the hardened concrete:

- Concrete was properly consolidated and cured.
- Overall strength properties, as indicated by paste hardness and paste-aggregated bond, were excellent.
- The Portland cement was sufficiently hydrated.
- The water-to-cement ratio of the concrete appeared to be low.
- The depth of carbonation (from the exterior surface) ranged from minor to moderate.
- No deleterious reactions were detected in the concrete.
- Very few small shrinkage cracks were present along the exterior surface.

Shrinkage of Concrete

Virtually every concrete is subjected to shrinkage. Shrinkage is the time-dependant decrease in concrete volume compared to its original placement volume. Shrinkage results from physical and chemical changes that occur in the paste fraction of concrete. The two principal types of shrinkage are plastic and drying shrinkage. Plastic shrinkage occurs while concrete is in the plastic state. Drying shrinkage occurs after concrete has reached initial set.

Drying shrinkage in concrete is caused by the loss of moisture in the paste. It is influenced by a variety of factors, including:

- Environmental conditions (temperature and relative humidity).
- Size of the member (surface area to volume ratio).
- Concrete material factors.
- Volume of aggregate.
- Elastic modulus of the aggregate.
- Water/cementitious ratio (w/cm) of the paste.

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\(^1\) According to ASTM C856-04. “Standard Practice for Petrographic Examination of Hardened Concrete.”
\(^2\) Core B, drilled from north wall about 52-away from the northwest corner.
Normally all concrete structures are subject to some form of restraint, such as steel reinforcement or forms. As the concrete cures following the exothermic reaction, it cools and thus decreases its volume. As concrete begins to lose volume, the restraint inhibits movement, which then induces tensile stress in the concrete. Once the tensile capacity of the concrete has been exceeded, the concrete cracks. In most cases, cracking is not a major concern and is normally controlled with as adequate amount of properly distributed reinforcing bars (rebar). Proper addressing of temperature and shrinkage dimensional changes is extremely important in applications such as containment structures. In such properly controlled situations a large number of narrow cracks rather than a few wide cracks are formed. ACI standards provide essential information and guidance on minimizing shrinkage of concrete and subsequent cracking.

The minimum wall thickness and the minimum amount and spacing of reinforcement to be used in structural floors, roof slabs, and walls for control of temperature and shrinkage cracking is given in ACI 318\textsuperscript{3} or in ACI 350R\textsuperscript{4}. According to ACI 318-05 section 7.12.2.1:

Area of shrinkage and temperature reinforcement shall provide at least the following ratios of reinforcement area to gross concrete area, but not less than 0.0014:

- (a) Slabs where Grade 40 or 50 deformed bars are used \[0.0020\]
- (b) Slabs where Grade 60 deformed bars or welded wire fabric (plain or deformed) are used \[0.0018\]
- (c) Slabs where reinforcement with yield stress exceeding 60,000 psi measured at a yield strain of 0.35 percent is used \[0.0018 \times \frac{60,000}{f_y}\]

On the other hand, according to ACI 224R-01, Control of Cracking in Concrete Structures, the control of shrinkage cracking consists of reducing the cracking tendency to a minimum, using adequate and properly positioned reinforcement, and using control joints. In section 3.5.2, it states, “Properly placed reinforcement, used in adequate amounts, will reduce the number and widths of cracks, reducing unsightly cracking. By distributing the shrinkage strains along the reinforcement through bond stresses, the cracks are distributed so that a larger number of narrow cracks occur instead of a few wide cracks….”

Hence, the minimum-reinforcement percentage, which is between 0.18% and 0.20%, does not normally control cracks to within generally acceptable design limits. To control cracks to a more acceptable level, the percentage requirement needs to exceed about 0.60%. Reasonable crack widths for reinforced concrete structures based on the exposure condition are listed in Table 4.1 of ACI 224R-01 as illustrated below.\textsuperscript{5}

\textsuperscript{3} ACI 318-05/318R Building Code Requirements for Structural Concrete and Commentary
\textsuperscript{4} ACI 350-01/350R-01 Code Requirements for Environmental Engineering Concrete Structures and Commentary
\textsuperscript{5} Accordingly reasonable crack width for water-retaining structures is 0.004-in. The observed cracks in the Pomona water tank are about 16 to 8 times greater than this value.
Table 1  Guide to reasonable* crack widths, reinforced concrete under service loads

<table>
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<th>Exposure condition</th>
<th>Crack width</th>
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<tr>
<td>Dry air or protective membrane</td>
<td>0.016</td>
</tr>
<tr>
<td>Humidity, moist air, soil</td>
<td>0.012</td>
</tr>
<tr>
<td>Deicing chemicals</td>
<td>0.007</td>
</tr>
<tr>
<td>Seawater and seawater spray, wetting and drying</td>
<td>0.006</td>
</tr>
<tr>
<td>Water-retaining structures†</td>
<td>0.004</td>
</tr>
</tbody>
</table>

* It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement.  
† Excluding nonpressure pipes.

For the case of Pomona water tank the reasonable shrinkage crack width is about 0.004–in (~1/240 in). Based on the spacing of the construction joints and ACI 350R-01 (Table 7.12.2.1), the minimum shrinkage and temperature reinforcement should be at least 0.4%\(^6\) of the gross area of concrete. In case of the exterior walls, both in N-S and E-W walls, the ratio of the area of the horizontal reinforcement to the gross area of concrete is about 0.28%. This is significantly lower than the ratio required by ACI 350R-01. It is the horizontal reinforcement that is needed to prevent excessively wide vertical cracks, such as those observed at the Pomona Reservoir 5C.

**Cracking Analysis**

The as-designed conditions were modeled to address temperature and shrinkage volumetric changes of the concrete versus constraint provided to the wall structure. The cross section of the wall presented in Figure 2 was subject to analytical modeling of temperature changes representing shrinkage and temperature differentials. Figure 5 presents the stress distribution due to differential movement between the relatively stiff foundation and the still gaining strength wall. Figure 6 presents the calculated crack width and the length of the vertical crack from the bottom of the wall. It can be seen that the as-designed wall was to crack to a substantial width and to the height of several feet from the ground. Because the wider cracks present are likely to let water through the wall, corrosion of reinforcement is likely to occur, thus compromising the integrity and safety of the tank.

\(^6\) This ratio is for Grade 60 reinforcing bars
resulting deformation and stresses

“free“ unrestraint shortening of fresh wall due to cooling, shrinking...

bond between wall & foundation

older stiff foundation

Figure 5. Mechanism of stress development in the wall subject to temperature and shrinkage shortening.

Figure 6. Crack width, length above wall base, and steel stress upon wall shrinkage equivalent to 15°K temperature drop.
Concluding Remarks

- The wall cracking observed in the Reservoir 5C creates unacceptable risk to reinforcement corrosion and eventual safety of the wall.

- The crack length and width is consistent with the design/construction of the wall.

- The walls require intensive maintenance program to identify and seal cracks of excessive width (0.1 mm) or the walls should be sealed from inside with a water-tight membrane.

- The roof deck shows an excessive amount of cracking which should not be left unattended. Therefore, the roof deck coating should be considered for long-term maintenance.