Confirming Shotcrete Quality On Site

by Steven H. Gebler and George W. Seegebrecht

Construction workmanship contributes significantly to the quality of any concrete project, but it plays a particularly important role in shotcrete projects. Preconstruction testing of cores taken from sample panels can help flag some potential material problems, but the shotcrete crew's technique determines the quality of the project. Fortunately, methods have been developed to examine, sample, test, and evaluate the quality of in-place shotcrete, as well as to determine the causes of distress or deterioration. This article recounts investigations into several shotcrete pool projects that exhibited various problems and explains the findings and their significance in each case.

Examining the Cause of Low Core Compressive Strength

A residential swimming and wading pool in the southwestern U.S. exhibited sand seams, voiding, and other defects. Preliminary testing indicated that in-place materials did not meet the specified compressive strength of 4500 psi (31 MPa). An investigation of the cause of low strength began with a review of project documents, including laboratory test results, mixture design information, correspondence, and drawings associated with the pool construction.

During a site visit, investigators examined the shotcrete's appearance and hammer-sounded the pool surfaces to note obvious problems with the overall integrity of the pool shell. The overall surface appearance was good; some localized cracking was noted, but it was not excessive.

Hammer sounding of both pool shells indicated that most walls were solid or sound. Isolated areas, however, did exhibit hollows and associated cracking that seemed to indicate the presence of subsurface delaminations.

Cores were taken not only to determine compressive strength, but also to assess the quality of the in-place shotcrete by examining the core's overall compaction and degree and location of voiding. Three cores were taken at each wall and the pool floor.

The cores were returned to the laboratory for further examination and testing. The authors observed that the shotcrete was not consistently applied to provide the proper compaction. In an effort to quantify this observation, not as a post-placement acceptance criterion, the team graded the cores on the scale of 1 to 5 (good to bad, respectively) according to the Core Grading System presented in ACI 506.2, "Specification for Shotcrete," Section 1.7. Seven of the 15 cores were judged an average grade above 2.5, and ten other cores were graded above 3. Generally, core grades above 3 are judged as unacceptable for structural grade shotcrete.

The cores exhibited considerable voiding as shown in Fig. 1. The voiding was significant in two regards. First, the voids reduced the unit weight of the shotcrete, which resulted in a corresponding strength reduction. Second, the location of the void immediately below the surface would

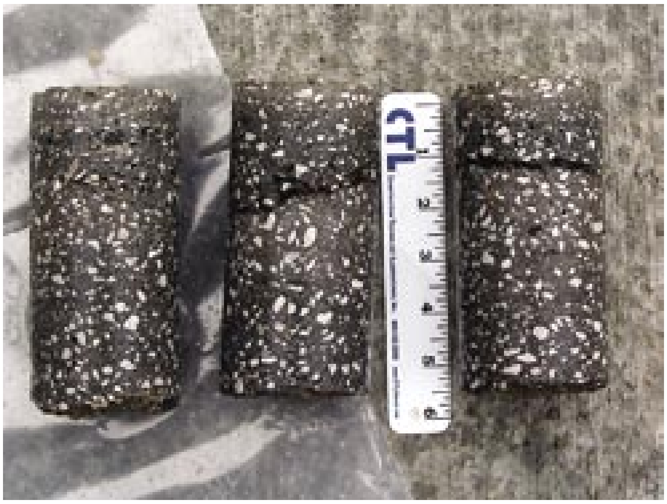


Fig. 1: Wading pool cores indicated significant voiding approximately 1 to 2 in. below the surface

Fig. 2: Typical shotcrete core from pool during compression testing

likely have adversely affected the performance of the tile system yet to be installed.

Cores were then tested in compression in accordance with ASTM C 42 (see Fig. 2). Core compressive strength averaged 2100 psi (14 MPa), just 47% of the specified 4500 psi (31 MPa). This strength did not comply with the specification. A greater concern, however, was that higher strengths (lower water-cementitious material ratio [*w/cm*]) were needed for long-term durability in the high-sulfate soils found in the southwestern states.

To determine the cause of these low strengths, core samples underwent petrographic examination to evaluate the shotcrete properties. Petrographic analysis found a *w/cm* estimated to be surprisingly higher than desired: approximately 0.60 versus the approved mixture design value of 0.45. This high *w/cm* was unusual for shotcrete, because such a high ratio would likely result in sloughing of the material when applied.

Together the high *w/cm* and the degree of voiding reduced compressive strength to the degree indicated by the average core strengths.

Explaining Pool Liner Cracks

A contractor applied wet-mix process shotcrete over an existing pool shell at an apartment complex in New York State. Shortly thereafter, the shotcrete liner reportedly developed cracks. One local consultant, unfamiliar with shotcrete, who was called in to investigate asserted that the shotcrete did not meet project specifications and that the cracks were structural in nature.

Approximately 2 years later, CTLGroup also conducted an on-site inspection of the pool in question, to observe its condition and mark areas for later extraction of cores (see Fig. 3 and 4). Subsequently, cores were extracted for examination.

Based upon that on-site inspection, the examination of cores, and a review of project documents, CTLGroup presented the following findings:

- The contractor had been denied access to the shotcrete pool liner after the application, which resulted in the pool being improperly cured. This circumstance led to the development of nonstructural drying shrinkage cracks in the pool liner;
- The lack of curing also hindered the strength development of the shotcrete. Higher strengths would have been attained had the shotcrete been adequately cured. Even so, core tests confirmed that compressive strengths met the contract and project requirements;
- The cores extracted from the new pool liner under the author's supervision were graded in accordance to ACI 506.2-95, Specification for Shotcrete. The Core Grade ranged between 1 and 2, indicating in-place structural-grade shotcrete that meets the requirements of ACI 506.2-95.

The investigator's report stated that the nonstructural cracks in the new pool liner could easily be repaired and, with a final application of a marcite coating, could render the pool usable. The owner hired a very knowledgeable shotcrete expert who confirmed CTLGroup's findings.

Discovering Flexural Movement

Local authorities engaged a contractor to rehabilitate a municipal pool in a Chicago suburb. The work consisted of applying a new shell of shotcrete

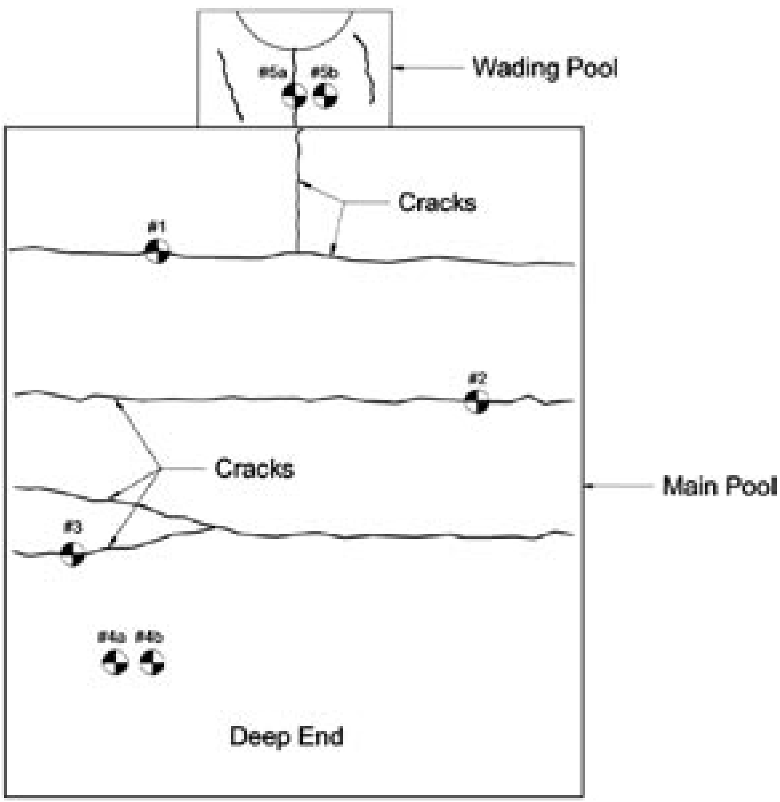


Fig. 3: Schematic of New York apartment pool showing observed cracks and core locations

Fig. 4: Cracks observed in main pool of New York apartment complex

to the existing reinforced concrete wall and floor, applying a white portland cement plaster coat (lining), and performing various plumbing, piping, painting, and other miscellaneous tasks. A little over a year later, some hairline cracks were noticed in the plaster coat. Further examination revealed additional cracking in the plaster lining and some delaminations between the plaster lining and the shotcrete shell. At the time, the cracking was attributed to drying shrinkage, and repairs were attempted using an epoxy mortar and pool paint to recoat the pool lining. However, new cracks continued to appear following these repairs.

CTLGroup was hired to determine—through examinations and measurements, hammer soundings, petrographic examinations of cores taken from the pool, and a review of pertinent documents—the cause of the distress observed in the pool. Evidence soon pointed to an explanation other than drying shrinkage as the cause of the cracking.

Surface cracking was observed over the entire shallow pool area. Although cracks were seen in all directions, most were oriented in the pool's longitudinal direction (east-west). Crack spacing in the pool floor was variable but averaged about 3 to 4 ft (0.9 to 1.2 m). If drying shrinkage had caused the cracks, the predicted spacing (based on the 24 to 36 times thickness rule) should have been about 12 to 15 ft (3.6 to 4.6 m).

Much of the original plaster liner had been replaced with an epoxy mortar, and the pool surface had been coated with white pool paint. Hammer sounding the surface revealed some bond loss under the remaining original plaster liner; some, but less, bond loss under the epoxy liner; and considerable bond loss around water inlets. No significant debonding was found in the pool walls.

Investigators focused considerable attention on cores, water inlets, and expansion joints:

Cores—Four-in.-diameter cores were taken to the full depth of the shotcrete shell for visual observation and for petrographic examination. Most cores were drilled to include a crack in the paint and liner. Observation of the cores disclosed a crack in the shotcrete shell directly under the crack in the liner. During coring, the operator could feel when the core drill had reached the bottom of the shotcrete shell. On removal of the core, a water-filled space was found between the shotcrete shell and the original concrete shell. No cracks were found in the original concrete shell. The spaces between the two shells, at the core holes, varied from 1/32 to 1-1/4 in. (0.8 to 32 mm) (see Fig. 5). The shotcrete appeared to be sound and of good quality. The direction of the cracks within the cores ranged from vertical to horizontal to angled. Phenolphthalein applied to the cores indicated that essentially no carbonation of the shotcrete had occurred, meaning that the shotcrete was relatively dense and compacted.

Water Inlets—All the water inlets appeared to have been pushed up from the floor level. The liner around each of the water inlets also sloped up to the inlet, with cracks radiating from the inlet (see Fig. 6). Most of the liner in these areas had been replaced with epoxy mortar, indicating that the original plaster liner had failed in the same manner and that the failure occurred even after application of the epoxy mortar. In other words, the shotcrete shell was continuing to move, and something had pushed the water inlets higher than their original position in the pool floor. Given that the 1-1/2-in.-diameter (38.7 mm) PVC distribution pipes were embedded in the shotcrete shell floor and the main distribution pipes were embedded in a chase in the original pool floor, it was clear that the water distribution system had been disrupted.

Expansion Joints—Investigators observed buckling failure at the expansion joints. The east expansion joint had raised up about 1/2 in. (12 mm) and caused cracking in the epoxy mortar joint repair and surrounding shotcrete shell. A joint space of only 1/16 in. (1.6 mm) was available, much too tight to allow for expansion due to normal temperature changes, which undoubtedly

Fig. 5: Wire probe inserted into the space between the original substrate concrete and shotcrete shell

Fig. 6: Measuring movement of water inlet above floor level

had caused buckling, cracking, and heaving at the joint area. Normal joint spacing should be around 1/2 to 3/4 in. (12 to 20 mm).

Petrographic examination of the cores supported the theory that cracks were due to structural movement rather than drying shrinkage of the shotcrete shell. Among the findings:

- Most cores exhibited diagonal and horizontal cracks typical of structural cracking caused by high shear forces;
- Most cracks in the shotcrete passed around and through the aggregate, indicating that cracks occurred after the concrete developed substantial strength and not at early ages;
- The paste was hard and the paste-aggregate bond was good; and
- The shape of cracks was typical of cracks caused by shear forces.

All the evidence gathered during the investigation pointed toward the following scenario to explain the pool's distress:

- The pool had not been properly winterized, that is, blowing out the water piping system, placing antifreeze in the pipelines and leaving at least 12 in. (0.3 m) of water in the pool;
- When water in the piping system later froze, it caused cracking in the piping system, which allowed water to leak into the unbonded space between the shotcrete and original concrete floor slabs. Subsequent freezing of this water expanded the space and caused the upper (shotcrete) slab to heave;
- Additional freezing-and-thawing cycles further expanded the space, which caused additional heaving of the upper slab and subsequent cracking of the shotcrete and cracking and delamination of the plaster lining; and
- Repairs to the failed plaster lining using epoxy mortar were not successful, as arching of the shell caused cracking in the lining and the shotcrete shell.

Detecting Poor Workmanship

The construction manager for the aquatic center at a Georgia school engaged CTLGroup to investigate reported defects in the swimming pool walls. There was also concern about the low compressive strength exhibited by cores obtained from the pool walls, which had been constructed with dry-mix process shotcrete. The investigation included review of contract documents and reports by others, examination and laboratory testing of cores (some untested and some previously tested by others), and structural analysis. The main purpose of the investigation was to determine the acceptability of the as-built swimming pool walls.

A review of the construction specifications revealed that wet-mix shotcrete was permitted as an alternative to cast-in-place concrete, provided the work was performed in accordance with ACI 506R. Shotcrete strength at 28 days was to be no less than 5000 psi (34 MPa) and workmanship was to be acceptable under the Core Grade System of ACI 506.2. The contractor chose a design-build approach. The design-build team further chose to reduce the design strength requirement to 3000 psi (20.7 MPa) and use dry-mix process shotcrete.

Prior to CTLGroup's involvement, the shotcrete contractor's investigators improperly conducted compressive strength testing. In their testing, they applied the compressive load normal to the sand lenses (see Fig. 7). The sand lenses were oriented at approximately a 30- to 40-degree angle relative to the pool walls. By testing normal to the sand lenses, which is contrary to ACI and ASTM shotcrete documents, these consultants arrived at an erroneous high strength.

A review of structural design drawings and calculations raised questions about the adequacy and placement of reinforcing steel for the pool walls. The reinforcing steel was designed for a condition corresponding to an empty pool with exterior soil pressure. This reinforcing steel is therefore placed nearest the soil side of the wall to best resist bending due to soil pressure with the pool empty. Another design condition commonly considered is a full pool with unbalanced exterior soil pressure. Accommodating both design conditions would generally be achieved by maintaining reinforcing steel approximately centered within wall sections or adding a second layer of reinforcing steel nearest the interior surface of the pool walls.

The investigators inspected several untested cores and others that were previously tested. All these cores contained sand lenses and were quite porous. Eight additional cores were requested, to be used for stress-strain tests. Prior to the testing,

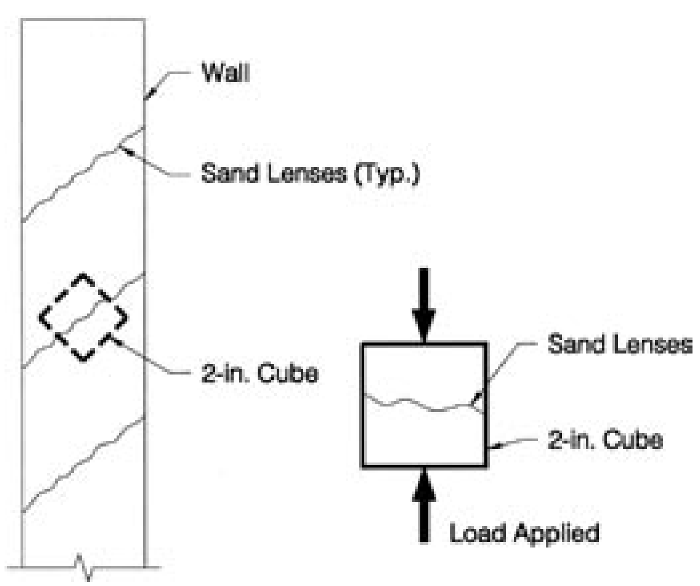


Fig. 7: Improper strength tests, with compressive load applied normal to sand lenses, yielded erroneously high strengths

investigators graded the cores according to the requirements in ACI 506.2. The mean core grade was greater than 3, which is unacceptable.

These cores had multiple sand lenses, high porosity, and entrapped rebound. Several cores also exhibited color differences attributable to changes in water-cement ratio during shooting (adjusting the water at the nozzle during shooting).

Based on examination of cores, the results of tests conducted by the author's firm and others, and structural analysis, the investigators reported that:

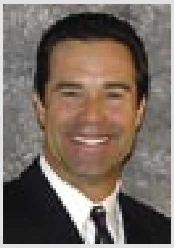
- When tested in accordance with ACI 506R and ASTM shotcrete documents, the in-place compressive strength of the shotcrete walls did not meet the minimum design compressive strength;
- The low shotcrete strength was due to the presence of multiple sand lenses at an angle to the vertical wall surface in pool walls. These defects in the in-place materials had weakened the pool wall. Besides the defective sand lenses, rebound and crumbly weak shotcrete were observed within pool walls;
- Structural analyses demonstrated that the sand lenses not only decreased the strength of the pool walls, but also had decreased the deformation capacity to a degree that a nonductile flexural failure could occur; and
- Design service life would be compromised as corrosion of steel reinforcement would likely become a problem. The porous shotcrete would inevitably be infiltrated with moisture, thereby corroding embedded steel reinforcement.

The team concluded that the as-built pool walls should be rejected and recommended that if shotcrete was used to redo walls, only a certified nozzleman should be allowed to do the work.

Conclusion

The investigations described here demonstrate a range of problems that can occur on shotcrete pools alone, just one type of structure. Knowledgeable investigators can apply a variety of tools and techniques either to confirm the quality of in-place shotcrete or to detect and explain deficiencies.

***Steven H. Gebler**, P.E., is a Senior Principal Engineer with CTLGroup in Skokie, IL. A current member of several ACI committees and Past Chair of ACI Committee 506, Shotcreting, and 308, Curing Concrete, he is a leading expert in shotcrete specification, curing, quality assurance, and evaluation.*



***George W. Seegebrecht**, P.E., is a Senior Evaluation Engineer with CTLGroup. A member of ACI and ASA, he has over 20 years of experience consulting on a wide range of issues relating to concrete and shotcrete design, placement, performance, and repair. Seegebrecht has been a frequent speaker for the National Spa and Pool Institute.*