Get the Air Out?

In 1957 and 1958, Armand Gustaferro was the manager of a plant that produced prestressed concrete beams and girders for 50 bridges on the Illinois Tollway. At that time, the maximum design strength given in ACI 318 was 3750 psi. Gustaferro, however, needed a compressive strength of 4000 psi at strand release and 5000 psi at 28 days. The tollway engineers were concerned that high-strength, air-entrained concrete could not be economically achieved on a daily basis. So they specified non-air-entrained concrete.

Would that happen today? Many producers of both prestressed and ready-mixed concrete are facing specified average total air contents that are 6% to 7%, or even higher, for freeze/thaw resistance in exterior vertical members. Engineers seem to believe that if a little air is good, a lot is better. There also seems to be confusion in the industry as to the correct exposure category for vertical concrete members. If air contents really need to be in the 4% to 7% range, Gustaferro's non-air-entrained concrete should have already been replaced. But it hasn't. Even today, Gustaferro is proud to say that the non-air-entrained beams and girders his plant made are still performing well.

Twenty-five years of service

In the summer of 1982, Gustaferro, Hillier, and Janney (Ref. 1) visually inspected 20 bridges on the Illinois Tollway. An item of particular interest was the durability of the prestressed concrete. The report indicated that, in general, the durability of the bridge girders had been excellent. The girders had been essentially maintenance free, and only minimal freeze/ thaw deterioration or rusting of reinforcement occurred. Most girders looked very much as they did when the bridges were first built in 1957.

Girders on one bridge in particular had suffered slight corrosion damage due to the penetration of deicing salts. The authors noted that there were layers of salt on the sides of some of the girders. In some areas the salt layer was as thick as 1/8 inch. Although there was corrosion damage, the authors noted no freeze/thaw deterioration in these girders.

Using a spinning process that precluded incorporation of entrained air, cylindrical prestressed concrete piles that served as the bridge piers were cast. The authors report that these piles also were in generally good condition and required little or no maintenance. After 25 years,however, some piers suffered freeze/thaw deterioration in the zone where passing vehicles had splashed deicing-salt solutions onto the piers. This would seem to confirm current ACI 318 requirements for air entrainment in areas in contact with deicing salts.

Portland Cement Association tests

At the Portland Cement Association, researchers made precast panels in their lab and tested them in a simulated outdoor environment. They also tested high-strength concretes using a more standard freeze/thaw test in water. Both test results indicated good performance for non-air-entrained concrete.

Panel tests. Isberner (Ref.2) investigated the resistance to freezing and thawing of precast panels with facing mixes consisting of white quartz aggregates and white portland cement. The cement content of these concretes ranged from 840 to 900 pounds per cubic yard, and the water-cement ratio was 0.40. Some of the concrete contained no air-

Field surveys and lab tests show that non-air-entrained concrete performs well, but ACI 318 requires a minimum air content

By Bruce A. Suprenant and Ward R. Malisch

Air entraining low-water-cement-ratio concrete for structures located outside of splash zones probably raises production costs needlessly. The good condition of 70-year-old non-air-entrained precast panels on this entryway column at Grant Park in Chicago—arguably the harshest freeze-thaw environment in the nation—attests to that.

PHOTOS BY EMIL WARNCKE

entraining agent. Other concrete panels contained an air-entraining agent, which in normal concretes would provide the recommended amount of air. But since the panel contained stiff mixes, the air-entraining agent produced no increase, or only a very small increase, in air content.

After a 7-day moist cure and 21 days of air drying, the panels were immersed face down for 24 hours in water $1/8$ inch deep. They were then mounted vertically and subjected to alternate freezing at 0° F and thawing in air at 73° F. Before each freezing cycle, technicians thoroughly wetted the exposed-aggregate facing concrete. None of the panels showed any sign of deterioration of the facing concrete after 125 cycles of freezing and thawing.

Freeze/thaw tests. PCA funded studies in 1960 and 1978 on low water-cement-ratio (0.30 to 0.40) moist-cured concretes (Ref. 3), and on low water-cement-ratio (0.33) simulated steam-cured concrete and moist-cured concrete (Ref. 4). These tests showed that even non-air-entrained concretes were very frost-resistant when air-dried before freezing and thawing in water.

For the non-air-entrained concretes, petrographers microscopically measured the air-void system. The maximum distance of any point in the paste to an air void (spacing factor) was measured as 0.02 inch. This is dramatically higher than the generally accepted 0.008-inch criterion for an adequate air-void system. The authors wrote, "These results indicate that, at water-cement ratios of 0.40 or less and for freezing and thawing in water, the usual requirements of the air-void system do not apply, probably due to the greatly reduced freezable water content, and to a lesser degree, to the increased tensile strengths of such high-quality concretes. The results are of considerable practical significance, particularly to the precast, prestressed industry, which sometimes experiences difficulty in obtaining the high strengths usually specified while providing the required air contents specified for durability."

Some ground-level non-air-entrained concrete at Chicago's Grant Park reveals distress that may be related to freeze/thaw cycles. But note the generally good condition of the precast balusters and the rail beneath them. Settlement of the structure caused the cracking seen at the right.

How much air?

ACI 318-99, "Building Code Requirements for Structural Concrete" (Ref. 5), requires concrete exposed to freezing and thawing or deicing chemicals to be air-entrained, with an air content as shown below for moderate exposures. ACI 318-99, however, indicates that for specified compressive strengths greater than 5000 psi, the air content can be reduced by 1.0%. And in the same section, the code also provides a tolerance of 1.5%. The table shows the minimum total air content required for moderate exposures.

As the table shows, the minimum permissible ACI 318 total air contents for moderate exposures to freezing and thawing are low. Typical air contents of non-air-entrained concrete are about 0.5% lower than the permissible minimums shown in the far right column in the table. For instance, the air content for a 3/4-inch maximum-size-aggregate, non-air-entrained concrete will generally be about 2%. The table shows that 2.5% is the permissible minimum. If a water reducer is used, which is quite likely, the measured total air content of the nominally non-air-entrained fresh concrete is likely to exceed the minimums. The air content that results from using a water reducer, however, may not provide the air-void-system properties needed for adequate freeze/thaw resistance.

The 1983 revision of ACI 318 was the first to specify total air content required for frost resistance, based on a classification of severe or moderate exposure. The accompanying commentary indicated that the required air contents were based on the recommendations in ACI 211.1, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" (Ref. 6). The ACI 211 definitions are as follows.

Moderate exposure: Service in a climate where freezing is expected but where the concrete will not be continually exposed to moisture or free water for long periods prior to freezing and will not be exposed to deicing agents or other aggressive chemicals. Examples include exterior beams, columns, walls, girders, or slabs that are not in contact with wet soil and are located such that they will not receive direct applications of deicing salts.

Severe exposure: Concrete that is exposed to deicing chemicals or other aggressive agents or where the concrete may become highly saturated by continued contact with moisture or free water prior to freezing. Examples include pavements, bridge decks, curbs, gutters, sidewalks, canal linings, or exterior water tanks or sumps.

ACI 211 also indicates that if a member is not continually wet and will not be exposed to deicing salts, lower air content values such as those for a moderate exposure are appropriate even though the concrete is exposed to freezing and thawing.

The ACI 318 commentary definition of moderate exposure (from 1983 until 1999), reads slightly differently: "A moderate exposure is where the concrete in a cold climate will be only occasionally exposed to moisture prior to freezing, and where no deicing salts are used. Examples are certain [emphasis ours] walls, beams, girders, and slabs not in direct contact with soil." Certain

Total air content for frost-resistant concrete

Nominal maximum aggregate size, in.	Moderate Exposure	With 1% reduction due to f'c > 5000 psi	With (1.5% tolerance
3/8	6.0%	5.0%	3.5%
1/2	5.5%	4.5%	3.0%
3/4	5.0%	4.0%	2.5%
1	4.5%	3.5%	2.0%
1 1/2	4.5%	3.5%	2.0%

A walk in the park proves our point

Thanks to its location in the low Upper Midwest and its proximity to Lake Michigan, which helps cause temperatures to fluctuate wildly, you'd be hard-pressed to find a harsher freeze/thaw environment for concrete than Chicago. It's such a harsh environment that you'd think precasters would want to air-entrain all exterior concrete, even if it weren't required, just for liability protection.

However, the condition of 70-year-old downtown concrete structures attests to non-air-entrained concrete's durability in non-splash zones. Leo Schlosberg, owner and president of Cary (Ill.) Concrete Products, requested a petrographic analysis of circa 1927 architectural concrete at Grant Park as his company prepared to do some renovation work there in the mid-1990s. The analysis revealed that the non-air-entrained exposed-aggregate concrete New York producer Benedict Stone used to cast walkway railings and entryway columns has a probable water-cement ratio of 0.40 and about 760 pounds of cement per yard.

Last summer, we took Schlosberg back to Grant Park to visually examine several hundred of the 1920s railing balusters and entryway columns. In the rare cases where balusters are deteriorating, the lower railings invariably reveal cracks from structural stresses, most likely due to settlement. (The park, located on what used to be the bottom of Lake Michigan, now sits on lake fill.) "Once stress cracks the concrete, water gets in and damages it," notes Schlosberg. When we examined the entryway column panels, any cracking we found was limited strictly to corners, again probably due to stresses from settlement. A couple of panels had popouts and a couple of inches of exposed rebar, but the cover was less than 1 inch thick in all cases.

The unblemished surfaces of both the balusters and the entryway columns support the belief that architects need not automatically specify air entrainment for exterior precast concrete.

— Don Talend

Leo Schlosberg, Cary Concrete Products: Rare cases of deterioration at Grant Park did not originate from freeze/thaw damage.

is a rather ambiguous term that could lead a conservative designer to assume severe instead of moderate exposure.

We agree with the ACI 211 definition that places vertical concrete in the moderate-exposure category unless it's in direct contact with wet soil or deicing salts. However, the abbreviated definition of moderate exposure in ACI 318 doesn't make it clear that if there is no exposure to wet soils or deicing salts, moderate exposure is the correct category.

ACI 301 is confusing

Unfortunately, both ACI 301-96 and 301-99 (Ref. 7) have the same language for specifying the total air content for concrete. Section 4.2.2.4 of ACI 301-99 states the following.

"Air content: Unless otherwise specified, concrete shall be air-entrained. Unless otherwise specified, air content at the point of delivery shall conform to the requirements for severe exposure."

ACI 301 contains the definitions for moderate and severe exposures in the Optional Requirements Checklist to the Architect/Engineer at the end of the document. This checklist is not included as part of the specification.

Many engineers and architects reference ACI 301 without additional air content information. Section 4.2.2.4 then requires all concrete (interior and exterior) to be air-entrained at the amount required for severe exposure. Obviously, it would be preferable to include more detailed air-content information in the specification that would allow interior concrete to be non-air-entrained and exterior vertical concrete to have air contents that fit the moderate-exposure category.

The high cost of air

We usually hear that air is free. But is it? ACI 211.1-91 states that "the use of normal amounts of air entrainment in concrete with a specified strength near or about 5000 psi may not be possible due to the fact that each added percent of air lowers the maximum strength obtainable with a given combination of materials." As the air content increases, therefore, producers add more cement to offset the strength reduction.

For strand release, most prestressed concrete producers need 4000- to 5000-psi compressive strengths in 24 hours. The 28-day compressive strengths range from 6000 to 8000 psi. As a general rule, 1 percent of air reduces 28-day compressive strength by about 5.0%. The 1.5% increase in air content needed to meet requirements for severe instead of moderate exposure produces a strength loss of about 450 psi. It takes about 50 pounds of cement to avert this loss.

For higher-strength concretes, the strength loss due to unnecessarily high air-content requirements increases, as does the cost of increasing the cement content to offset that loss.One producer estimates that it costs an extra $2 per cubic yard for concrete that meets the air-content requirement for severe, instead of moderate, exposure.

Don't pay if there's no problem

What happens when the air content for vertical concrete is lower than specified? On behalf of the owner, the engineer or architect may pursue one or more of the following remedies:

- An extended warranty
- Application of sealers or coatings to prevent saturation of concrete by water
- A payment reduction to cover potential future maintenance or repair

In the worst case, the engineer may insist on removal and replacement of the concrete.

These remedies may sometimes be justified when the air-content requirements don't meet those for moderate exposure since the concrete may not perform satisfactorily. However, if the engineer has specified air contents for severe exposure, when air content for a moderate exposure is appropriate, a warranty or pay reduction may not be necessary or reasonable. The field and laboratory data we've cited show that vertical concrete with a low air content can perform satisfactorily in a freeze-thaw environment.

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