Delamination: The Sometime Curse of Entrained Air

By Dipayan Jana and Bernard Erlin

Air entrainment in concrete was discovered accidentally about 70 years ago. Since then, entrained air has provided many blessings to concrete such as increased workability at lower water-cement ratios and reduced bleeding. And there is its primary function: maximizing the resistance of hardened concrete to damage from cyclic freezing and deicing chemicals.

There are also, however, some negative effects of air entrainment: there is one more concrete batch item that needs be controlled, there is a slight reduction in concrete strength, and there is the need to adjust to changes in timing and finishing techniques. In general, our industry has learned to accommodate the negatives relatively well. However, one of the difficulties of working with air entrainment has become a curse: delamination of hard-troweled concrete surfaces.

Delamination is a "plane" of separation between the surface layer and main body of concrete. Some common causes of delamination are corrosion of reinforcing steel bars aligned at a given depth, inadequate design and bonding of topping slabs, cyclic freezing, and improper finishing. This article deals only with delamination caused by hard-trowel finishing of air entrained concrete slabs.

Entrained air is essential for freeze/thaw durability and should be kept within industry guidelines (for example, 6±1½ percent with ¾ to 1 inch maximum-sized aggregate). Entrained air is unnecessary for concrete that will not be exposed to cyclic freezing unless there is a need to capitalize on its other blessings. However, there are numerous instances where machine-troweled slabs designed for use in nonfreezing environments contain entrained air where its blessings lead to the curse of delamination.

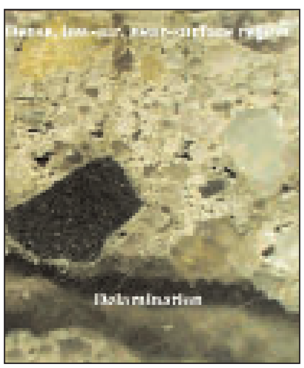
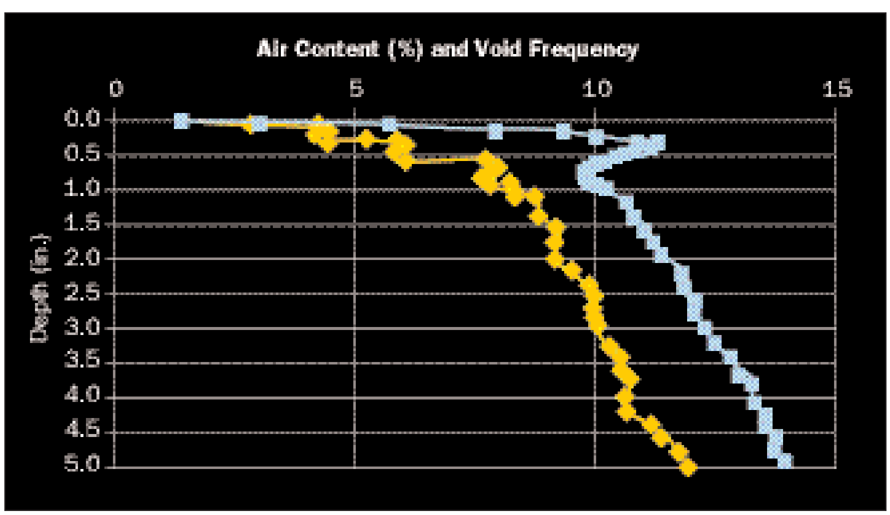


Figure 1, left: The cross section on the left shows a surface region from the warehouse floor where a dense low-air mortar devoid of coarse aggregate particles is underlain by a delamination plane. Air-entrained concrete in the rest of the core is shown on the right. Figure 2, below: These figures show profiles of air and paste contents of the core shown in Figure 1—the warehouse floor. The decreased air content (left) and increased paste content (right) in the top inch are due to finishing manipulations that washed air out of the surface region and forced coarse aggregate particles deeply into the concrete.



The following three case studies describe slabs that were designed to have dense, hard, flat, wear-resistant surfaces, but ended up delaminating due to entrained air and machine troweling.

Warehouse floor

A 5-inch-thick warehouse slab that incorporated a loading dock was placed on plastic sheeting. The loading dock concrete was designed to be air-entrained (5±1 percent air) because it was outside and would be subjected to cyclic freezing; it was given a broom finish. The interior slab was to be non-air-entrained because it would never be exposed to cyclic freezing; it was machine troweled. Apparently, the designer recognized that air-entrained concrete should not be machine-troweled.

Inadvertently, however, the air-entrained concrete mixture used for the loading dock was continued into the interior slab; the switch to non-air-entrained concrete was not made. Within a year after completion, large areas of the interior slab surface delaminated.

Cores were taken from both delaminated and non-delaminated areas for petrographic examinations. This revealed that the concrete was dense, well-consolidated, air-entrained, and had portland cement contents of about 6½ bags per cubic yard and water-cement ratios estimated to be:

- 0.40 in the top 1/8 to 3/16 inch
- 0.46 to 0.48 from 3/16 to 1/2 inch
- 0.44 in the rest of the concrete

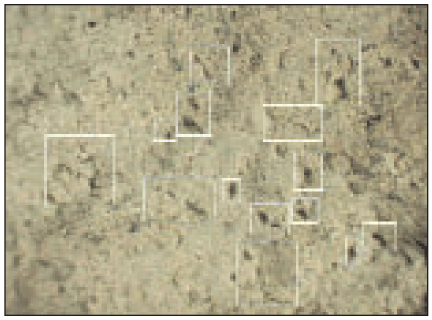
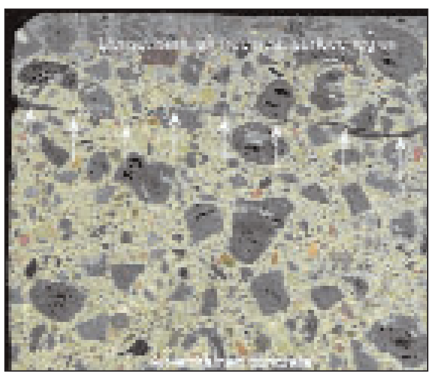


Figure 3. Concrete in the underside of the delaminated concrete from the warehouse floor has irregularly shaped and elongated voids that indicate there was trapped bleed water (boxed areas).

The air content in the body of the concrete was determined to be 12 to 13 percent—significantly higher than the 5±1 percent specified for the loading dock concrete. This excessive air entrainment gave the paste and coarse aggregate sockets a frothy texture that significantly reduced the concrete strength.

In the top 1/8 to 1/16 inch, the concrete contained:



- no coarse aggregate
- air contents of 1% to 2% (Figs. 1 and 2) versus 12% to 13% in the body of the concrete
- paste that is darker, harder, and has a water-cement ratio of 0.40 versus 0.44 in the body of the concrete
- paste contents higher than in the main concrete body: 38% versus 22% (Fig. 2)

We concluded that the absence of coarse aggregate particles, decreased air contents, lower water-cement ratios, and increased paste contents in the surface layer is due to hard and prolonged finishing manipulation that squeezed out some of the water, washed out air voids, and forced coarse aggregate particles downward.

The delamination plane is horizontal, parallel to the finished surface, and at a depth of about 1/4 inch (Fig. 1). On the underside of the delaminated surface layer are many fine, irregularly shaped, horizontal, elongated voids (Fig. 3), and in the concrete below the delamination are fine, vertical channels that terminate at the delamination plane. Our opinion is that the elongated voids and channels were caused by trapped bleed water. These features demonstrate that finishing occurred before the concrete had stopped bleeding. The higher water-cement ratio paste sandwiched between the lower water-cement ratio paste above and below indicate that finishing manipulations trapped bleed water below the surface and that finishing continued after bleeding stopped, which

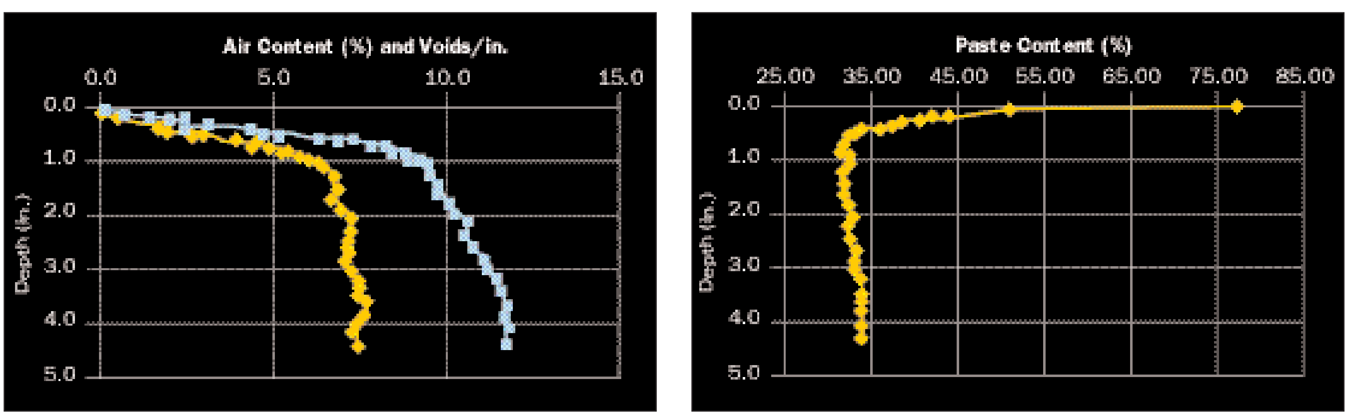


Figure 4, top: This cross section of a core from the lightweight floor slab shows: (a) a dark, low water-cement ratio, air-free near-surface mortar (top); (b) a delamination plane at a depth of 1/2 inch (arrows); and (c) lightweight coarse aggregate particles. The scale is in 1/16-inch increments. Figure 5. These profiles are of air and paste content measured in the cores shown in Figure 4. The decreased air content (left) and increased paste content (right) in the nominal top 1 inch are due to finishing manipulations that washed air out of the surface region and forced coarse aggregate particles deeply into the concrete.

created the very low water-cement ratio at the surface.

Normal air entrainment slows bleeding so that the sheen due to bleed water does not appear at the surface as quickly as in non-air-entrained concrete. Excessive air entrainment, as was present in this slab, slows bleeding even more. This was probably unanticipated and unrecognized by the finishers.

Because air-entrained concrete is sticky, it finishes differently than non-air-entrained concrete. In this situation, the finishers probably anticipated the proper finishing time based on past experience and used hard-troweling techniques on the air-entrained concrete. Unfortunately, it did not work, leading them to excessive surface manipulation in an attempt to get smooth surfaces. Compared with concrete placement on absorptive subbase (where some water is removed), placement on plastic sheeting increases bleeding. For this concrete, it was probably impossible to attain the desired surface without creating delamination.

Lightweight floor slab

An elevated concrete slab made with lightweight coarse aggregate was placed on metal decking and was designed to be air-entrained to reduce the concrete weight to meet dead load requirements. The slab was 5 inches thick and received a hard-trowel finish. Delaminations were detected shortly after the slab was placed in service.

Petrographic examination of a core from a delaminated area revealed that the body of the concrete:

- is air entrained, well consolidated, and made using expanded clay lightweight coarse aggregate
- has a cementitious materials content equivalent to 7 to 7½ bags of portland cement per cubic yard, of which 10 to 15% is fly ash
- has a water-cementitious materials ratio estimated to be 0.44 to 0.46
- has an air content of 7.3%
- has a paste content of 30%

The top ⅛ to 3⁄16 inch, however, varies from the rest of the concrete because:

- it is essentially devoid of the larger coarse aggregate particles
- the paste is darker (Fig. 4), harder, and has a water-cementitious materials ratio of 0.38
- it has an air content that is essentially zero (Fig. 5)
- it has a paste content of 40%

At a depth of ½ to ⅝ inch is a continuous delamination "plane." In the concrete flanking the delamination plane are short, isolated, discontinuous, elongated, and stringy air voids up to ¼ inch long that represent "incipient microdelaminations" that formed as a result of a coalescence of air voids caused by finishing manipulations. Imprints in the bottom surface of the delamination represent entrapped bleed water. The delamination is the result of hard finishing air-entrained concrete before bleeding stopped.

The reports published by ACI Committees 301 and 302 dictate that entrained air be excluded from concrete slabs whose surface will be machine-troweled—but there is silence with respect to lightweight concrete. The need for air-entrainment of lightweight concrete that will not be exposed to cyclic freezing is usually for decreasing dead loads. Although this need cannot be met typically without air entrainment, caution must be used in finishing such surfaces—hard and prolonged troweling should be minimized, if used at all.

Floor slab with metallic surface hardener

A warehouse floor was constructed with air-entrained concrete on which an integral metallic surface hardener was used to increase wear resistance. The hardener was applied to the surface as a dry shake. Within a year, areas of the floor cracked and "sheets" of the concrete surface delaminated. A chain-drag survey revealed that almost 70 percent of the floor was delaminated.

To investigate the cause of the delamination, cores were taken for petrographic examinations. We determined that the concrete:

- is air-entrained and air contents are from 5.3 to 6.6%
- portland cement contents are 6 to 6½ bags per cubic yard
- steel and polypropylene fibers are uniformly distributed throughout the concrete
- the water-cement ratio is variable from 0.25 in the surface layer where the shake had been worked into the surface to 0.43 in the rest of the concrete
- the shake consisted of portland cement, fine quartz sand, and short (about ¼ inch long) steel fibers
- the interface between the shake and the concrete is somewhat gradual (Fig. 6) because the shake was partially worked into the concrete.

A single, continuous, horizontal separation at a depth of ½ inch defines the "plane" of delamination. Along the top and bottom of aggregate particles in the area of the delamination are isolated, stringy voids (separations). These features are the result of hard troweling that removed air voids and also caused coalescence of air voids below the dry-shake layer. Separations along the top and bottom of coarse aggregate particles were a result of their slight movement in semi-rigid paste during application of the dry shake. In the main body of the concrete, the air content is nominally 5%; that decreases to essentially zero in the surface layer (Fig. 7).

The petrographic data tells us that the following sequence of events probably occurred:

- the dry shake was applied to air-entrained concrete just as it was beginning to stiffen
- heavy and prolonged machine troweling was used to work water from the body of the concrete into the shake
- because of the air entrainment, bleeding was minimized in a sense that is desirable because the small amount of water available to hydrate cement in

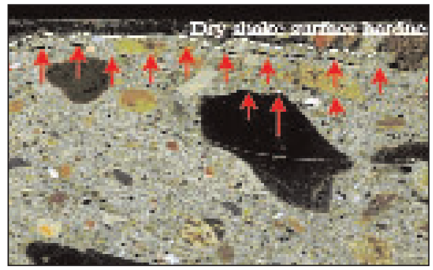
the shake resulted in a very low water-cement ratio

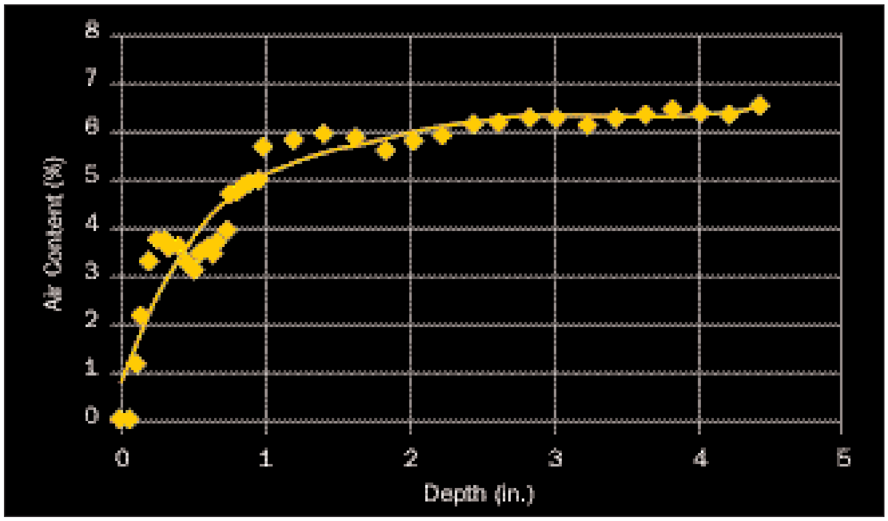
- heavy, prolonged finishing manipulations caused coalescence of entrained air voids into horizontal stringy units that caused the delamination.

Lessons

Delamination of machine-troweled slabs has become a major problem in our industry. The American Concrete Institute addresses entrained air in Committee Report 302.1R, Guide for Concrete Floor and Slab Construction: "Intentionally entrained air should not be incorporated in normal-weight concrete slabs which require a dense, polished, machine-troweled surface." We would add that "unintentionally" entrained air should also not be incorporated. ACI Committee Report 301, Specifications for Structural Concrete states that: "Concrete for trowel-finished interior concrete floors made with normal weight aggregates should not include an air-entraining admixture; the maximum air contents for these concretes should nor-

Figure 6, right: This cross section of a core shows the dry shake layer and the delamination plane below the shake (red arrows). Figure 7, below and next page: These profiles are of air and paste contents of the concrete shown in Figure 6. The decreased air content and increased paste content in the top 1 inch are due to finishing manipulations that washed air out of the surface region.

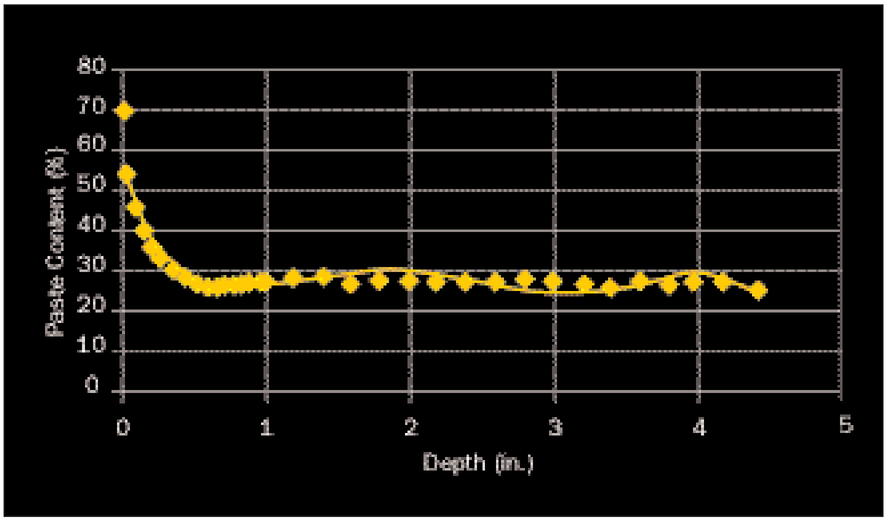




mally be 3 percent." Unfortunately, there is silence about lightweight concrete, where air-entrainment is used to reduce dead loads.

We regularly encounter delamination problems involving machine-troweled concrete slabs, both normal-weight and lightweight, that are air-entrained and air-entrained slabs on which integral shakes were used. In addition to problems caused by air entrainment, a recurring problem is finishing before the cessation of bleeding and finishing after concrete has attained significant set.

Slabs that will be heavily troweled should not contain entrained air because of the probability that delamination will result. If entrained air is necessary because concrete will be exposed to cyclic freezing during its early life, or because lightweight concrete is needed for structural purposes, the use of well-graded and "hard" fine aggregate, minimum entrained air content, water-reducing admixtures, and other means for lowering water-cement ratios along with light troweling will increase wear resistance and minimize the potential for delamination.



Bleeding should be minimized by using well-graded aggregates, and finishing should never start until bleeding has stopped. It should be recognized that surface crusting does not represent the condition of the overall concrete, and pan floats should not be used prematurely. Air-entrained concrete bleeds slowly, which increases the probability of finishing before bleeding stops. ■

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