Concrete, Construction, or Salt—Which Causes Scaling?

Part I: Importance of air-void system in concrete

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Scaling of concrete pavements, sidewalks, driveways, decks, and other slabs is a common problem in outdoor construction exposed to severe winter weather and deicing salts. Very often, the blame circulates around the quality of the concrete supplied (to the supplier), the methods of construction used (to the contractor), or the salt applied for snow removal (to the owner). Among these three, the most common culprit is *assumed* to be the deicing salt. The dispute is usually settled by field investigation, detailed petrographic examinations, air-void analysis, chloride analysis of concrete cores or saw-cut sections from the scaled and sound areas of a slab, and investigation of the various factors responsible for scaling.

Part I of this article provides three case studies that demonstrate the roles of lack of air entrainment, improper air entrainment (coarse air-void system), and inadequate air entrainment (low entrained air content) in scaling. Part II will provide three case studies to show scaling due to the initiation of finishing prior to the cessation of bleeding, finishing in the presence of excess water at the surface, and prolonged finishing practices. A poor air-void system causes scaling of the concrete surface at saturated conditions during cyclic freezing and thawing. Finishing improprieties, on the other hand, can cause scaling, abrasion, or delamination even in the absence of cyclic freezing and thawing.

According to the ACI Committee 116 report on "Cement and Concrete Terminology," scaling is defined as "local flaking or peeling away of the near-surface portion of hardened concrete or mortar" and is rated as "light," "medium," "severe," and "very severe" depending on the loss of surface mortar down to depths of less than 5 mm (0.2 in.); 5 to 10 mm (0.2 to 0.4 in.) and exposure of coarse aggregate; 5 to 10 mm (0.2 to 0.4 in.) "with some loss of surface mortar surrounding aggregate particles 10 to 20 mm in depth"; and greater than 20 mm (0.8 in.), respectively.

For resistance to scaling in severe weather, concrete should be:

(a) "Adequately" air-entrained and made using well-graded, frost-resistant aggregates: the concrete should have an air content of 6 to 7% (±1.5%) (for normalweight or lightweight concrete having 1/2 to 1 in. [13 to 25 mm] nominal maximum-size aggregate and exposed to severe weather), a specific surface of at least 600 in.$^{-1}$ (24 mm^{-1}), and a maximum void-spacing factor of 0.008 in. (0.2 mm);

(b) Properly placed, finished, and cured: the concrete should be well consolidated; it should be finished properly without any entrapment of bleed water beneath the finished surface; it should not be over-finished or finished in the presence of excess water at the surface; and it should be well-cured to provide adequate cement hydration and necessary development of strength at the surface to create a dense, near-impermeable, moisture-tight concrete; and

(c) Mature: that is, the concrete should undergo a period of air drying and should attain a compressive strength of at least 28 MPa (4000 psi) prior to the first exposure to freezing and deicing salts. Air drying is necessary to minimize the amount of freezable

TABLE 1:
Factors that can cause scaling—a holistic approach. Shown are the 10 common factors (categorized into Concrete, Construction, and Design/maintenance) to consider for resistance to scaling

Three main pillars	Ten factors	Details	Requirement
Design/maintenance	10. Deicing salt	Causes scaling only in poor-quality or poorly constructed concrete unless salt is applied at an early stage before the attainment of maturity	Third
	9. Drainage	Poor drainage and water ponding increases the degree of saturation	
	8. Maturity	A compressive strength of at least 4000 psi (28 MPa) and at least a period of air drying before the first exposure to freezing and deicing salt	
Construction procedures	7. Curing	Inadequate curing? Curing procedure	Second
	6. Finishing	Premature finishing? Over-finishing? Finishing in the presence of excess water on surface?	
	5. Consolidation	Degree of consolidation (amount of entrapped air)	
	4. Placement	Method of placement	
Concrete quality	3. Strength and *w/c*	How dense and moisture-tight is the concrete?	First
	2. Aggregates	Size, grading, modulus of elasticity, and frost resistance	
	1. Air-void system	Air void distribution from the surface downward. Specific surface (How fine are the voids?); void-spacing factor (How close are the voids?); and air content (How much air? Does the concrete have enough air to provide 9 ± 1% air in its mortar fraction?)	

water in the concrete, and a strength requirement is needed to resist the freezing-related tensile stresses in concrete.

Concrete that fulfills *all three conditions* should be durable in winter even in the presence of salt. Concrete that lacks any one of these conditions is susceptible to scaling and even more so in the presence of salt.

CASE STUDIES

Table 1 provides a holistic approach of ten different factors categorized into: Concrete Quality, Construction, and Design and Maintenance that can cause scaling. Out of hundreds of case studies on scaling that I have investigated, poor air-void systems and/or finishing improprieties are found to be the two most common causes of scaling. Therefore, I have screened six classic case studies where: a) scaling was found to be due to either poor air-void systems in the concrete (Part I), or improper finishing practices (Part II); b) 3- to 4-in.-diameter (75 to 100 mm), through-depth core samples were collected from the scaled and sound areas, which were either from the adjacent panels of a sidewalk, a driveway slab, or from adjacent slabs exposed to similar environmental and deicing conditions; c) except for air and finishing, the other factors listed in Table 1 were not found to be responsible for scaling (for example, in all cases the concrete was made using frost-resistant aggregates, well cured, and mature prior to freezing); and d) detailed field investigations, petrographic examinations, air-void analyses, and chloride analyses were done; all background information of the projects, concrete mixture proportions, construction practices followed, and weather conditions during construction were documented for comprehensive study.

In all the case studies, the concrete slab was exposed to sodium- or calcium chloride-based deicing salts. Prior to the investigation, salt was alleged to be the cause of scaling. In all the cases, however, both the sound and scaled panels have similar chloride concentrations due to their presence in the same deicing conditions. Salt was found to have played only a secondary role in scaling. Poorly air-entrained concrete was selectively scaled in the presence of salt, whereas good quality, properly constructed, and matured concrete remained sound.

Concrete causing scaling—importance of air-void system

Table 2 provides the air-void parameters, water-cementitious material ratios (*w/cm*), and chloride contents of the scaled and sound cores of the following case studies. Air-void analysis was done using the modified point-count method of ASTM C 457 "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." The profiles of air-void parameters were determined by using the procedures of ASTM C 457 along a series of parallel traverse lines on a vertical cross section of a core, as well as on a series of parallel, circular cross sections at various depths of a core. The *w/cm* was estimated by using various physical, textural, compositional, and mineralogical properties of paste in the unknown concrete and by comparing these properties with the standard concretes of known *w/cm*. Detailed petrographic examinations were done all on samples according to ASTM C 856 "Standard Practice

TABLE 2:
SOME PETROGRAPHIC OBSERVATIONS OF THE CASE STUDIES DESCRIBED IN THIS ARTICLE

Case studies of scaling	Petrographic observations
Scaling due to cyclic freezing and thawing of nonair-entrained concrete in the presence of salts	Concrete does not have "entrained" air, which is the intentionally introduced fine, discrete, spherical or near-spherical air voids having sizes of 1 mm (0.04 in.) or less. It is not uncommon for a nonair-entrained concrete to "generate" a couple of such air voids, but their amount and frequency are low enough to distinguish them from those intentionally introduced. The scales have lenticular configurations with tapered edges. Scaling occurs by surface-parallel cracks that transect and circumscribe the aggregate particles.
Scaling due to cyclic freezing and thawing of inadequately air-entrained concrete in the presence of salts	Concrete has "entrained" air, but the total air content is less than the industry-recommended amount, and the entrained air content is low.
Scaling due to cyclic freezing and thawing of improperly air-entrained concrete in the presence of salts	Concrete has entrained air, and the total air content may fulfill the industry requirements, but the voids are coarse and wide-spaced—that is, the specific surface (< 600 in.$^{-1}$ or < 24 mm^{-1}) and void spacing factor (> 0.008 in. or > 0.2 mm) are outside the industry recommendations.

for Petrographic Examination of Hardened Concrete." Chloride content analysis was done by using the methods of ASTM C 1152/C 1152M "Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete."

Case study I: nonair-entrained concrete

A nonair-entrained concrete that is critically water-saturated and exposed to cyclic freezing and thawing is very susceptible to scaling. Because deicing salt increases the degree of saturation of concrete, the detrimental effect of salt is most severe in a nonair-entrained concrete. In some cases, severe scaling of a panel adjacent to a perfectly sound and air-entrained concrete panel was found to be due to the accidental lack of dosage of the air-entraining admixture in the scaled concrete batch (this usually occurs where a scaled panel is separated from a sound panel by a construction joint indicating delivery of a new batch of concrete after a pause). A frequent measurement of air during placement of each batch is thus essential to ensure the uniformity of the concrete quality. The first example in Table 2 shows such a case study where scaling was due to the absence of entrained air in the scaled core from a sidewalk. Figure 1 shows a cross section of nonair-entrained concrete that has scaled and the adjacent air-entrained concrete that was sound.

If the concrete is air-entrained, scaling can still occur if: a) the concrete has a coarse air-void system with a low specific surface (<600 in.$^{-1}$ or <24 mm^{-1}) and a large void-spacing factor (>0.008 in. or >0.2 mm)—the air content may or may not satisfy the industry requirements (6 to 7 ± 1.5%); and/or b) the useful "entrained" air content of the concrete is low (irrespective of the total air content), which usually reduces the specific surface and increases the void-spacing factor of the air-void system. I have encountered both situations frequently—in many cases, the total air content did conform to the so-called designed "total air" requirement, and yet the concrete had a poor air-void system. It became obvious that it is the number of the tiny entrained air bubbles and their void-spacing factor, which are much more important for scaling resistance of concrete than the volume of total air.

Case study II: air-entrained concrete with an improper air-void system

The second example in Table 2 shows a case study of scaling in a downtown concrete sidewalk exposed to severe winter weather and the heavy application of salt. The core from a sound panel has an excellent air-void system—the air content, specific surface, and void spacing factor all conform to the industry recommendations. The core from a severely scaled panel, though air entrained, has a low air content and a coarse air-void system with a low specific surface and a high void-spacing factor (Fig. 2). A coarse air-void system can occur due to a low dosage of air-entraining admixture, excessive mixing of the concrete, or retempering or excessive addition of water (the other causes of a coarse air-void system—for example, the presence of high-range water-reducing admixtures or cement-admixture incompatibility—were not present). In spite of deicing salt being the alleged factor for scaling, the chloride content was found to be similar in both scaled and sound cores (due to their similar salt exposures) and, in fact, was higher in the sound core. Scaling was initiated in the panels having improper air-void systems and became aggravated in the presence of salt. Although both sound and scaled panels

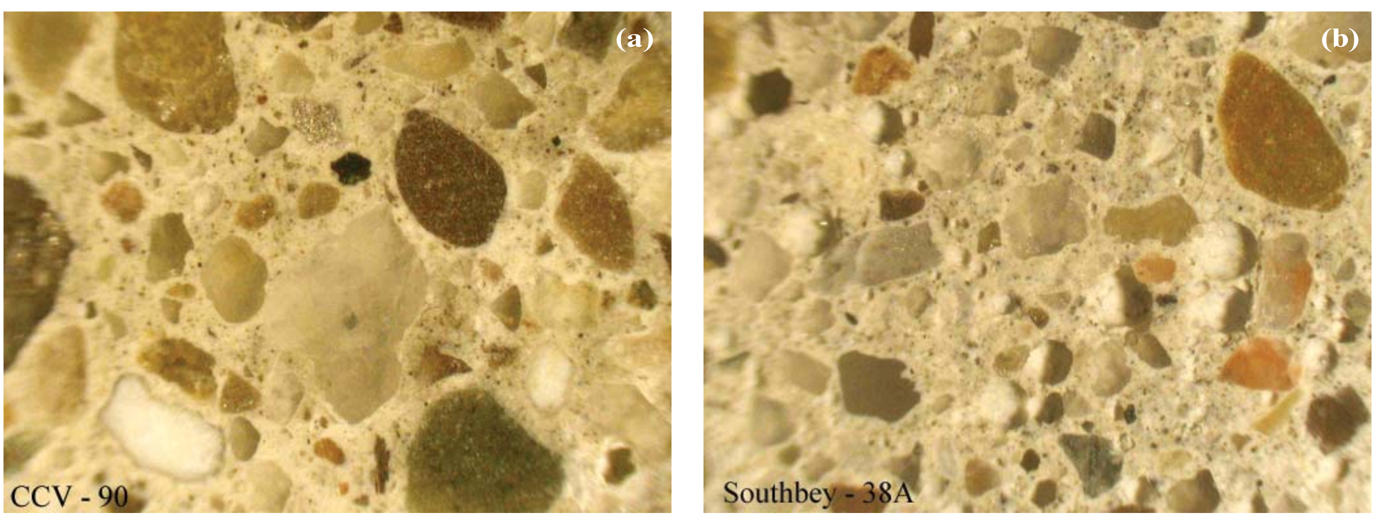

Fig. 1: Case study I: Air-void systems of nonair-entrained (a) and air-entrained (b) concretes from adjacent driveways. Scaling was due to the accidental escape of the air-entraining admixture in the concrete. The air-entrained concrete in the sound panel is prepared according to the mixture proportions and has performed satisfactorily

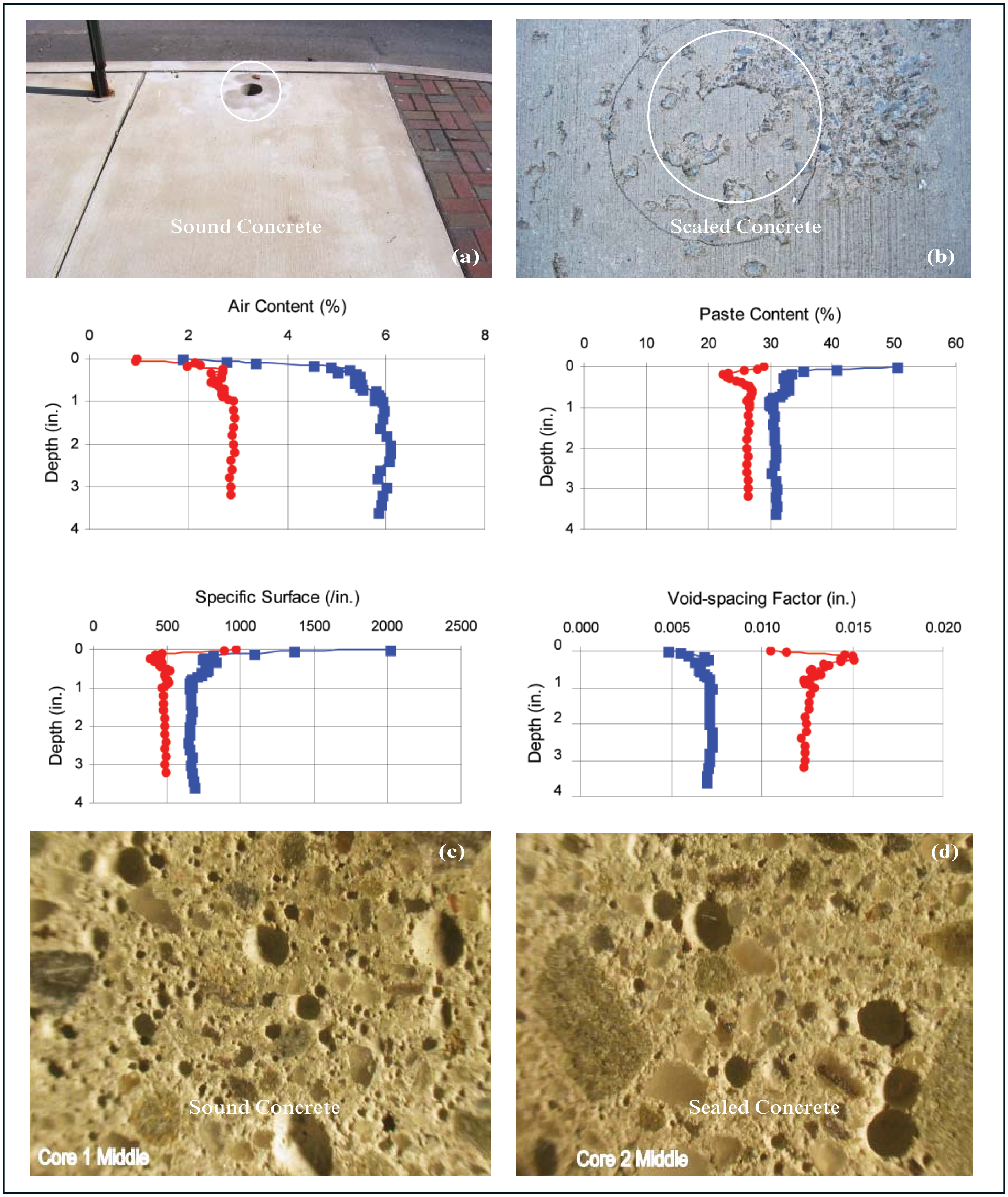

Fig. 2: Case study II: Scaling due to improper air entrainment (coarse air-void system with low air content and wide void spacing). Photos (a) and (b) show the surface conditions of panels where cores were taken; the graphs show profiles of air-void parameters in scaled (in red) and sound (in blue) concretes; and photos (c) and (d) show air-void systems in cross sections of sound and scaled cores. Note: 1 in. = 25.4 mm

experienced some finishing-induced loss of air at the surface, the air bubbles at the surface of the sound panel were still close enough to each other to provide the necessary protection of paste against distress due to cyclic freezing and thawing. This indicates that for scaling resistance, the air-void-spacing factor is more important than the air content. Figure 3 shows another very similar case where the "total air" content of the scaled core fulfilled the design air requirement, but the concrete still scaled due to such a coarse air-void system having widely-spaced bubbles.

Case study III: air-entrained concrete with inadequate entrained air

The third example in Table 2 and in Fig. 4 shows a case where a stamped concrete sidewalk has inadequate consolidation and, as a result, has more than the usual amount of entrapped air. The total air content again conformed to the design air, but the scaled panel had too little entrained air (<1%) to provide protection. The adjacent sound panel had 3% entrained air and 8.5% total air, which reduced down to 1.5 and 3.7% at the surface, respectively. Although the air-void system is coarse in the body, the surface has close-spaced bubbles to provide the necessary protection of the paste.

In all three cases: a) the sound cores have consistently slightly higher chloride contents than the scaled cores; and b) the chloride contents are significantly higher at the surface than in the body, which is consistent with the application of deicing salts. Concretes having poor air-void systems scaled, whereas those with good air-void systems were sound. Concretes in the panels having

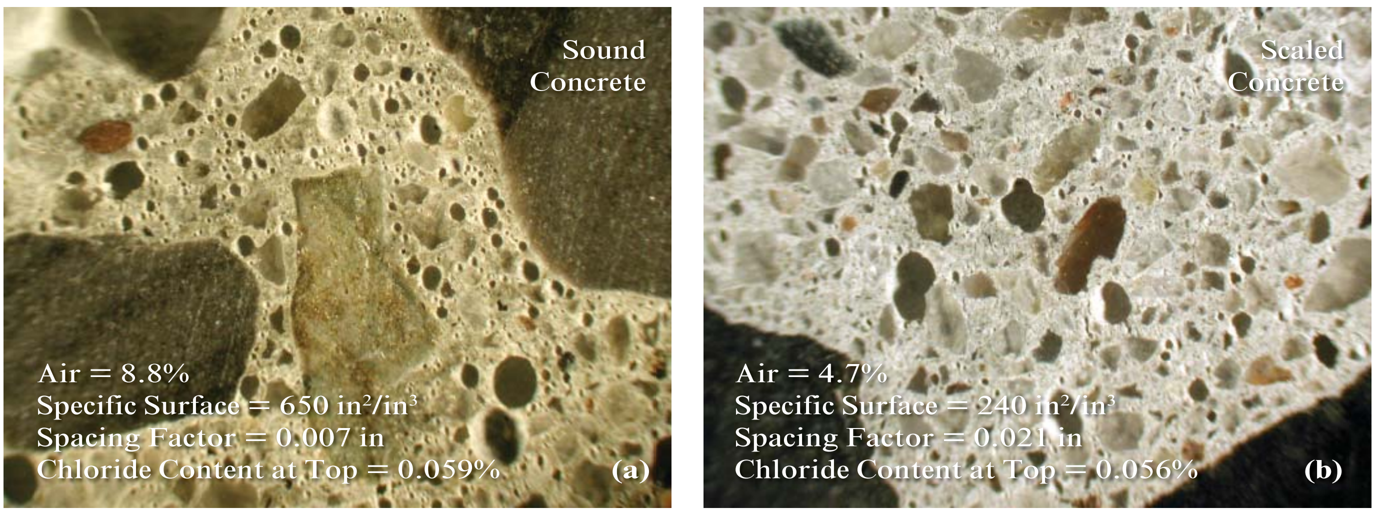

Fig. 3: Case study II: Scaling due to improper air entrainment (coarse air-void system with low air content and wide void spacing). Shown are air-void systems of sound (a) and scaled cores (b) and associated air-void parameters and chloride contents at the top 1/2 in. (13 mm)

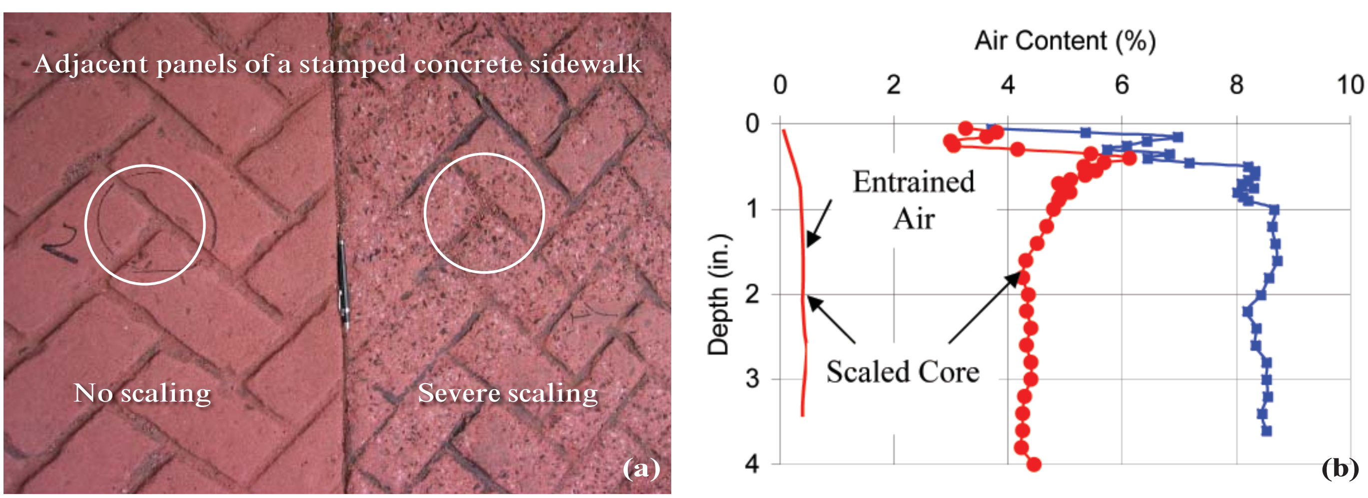

Fig. 4: Case study III: Scaling due to low entrained air. Two cores (a) taken from adjacent sound and scaled panels of a stamped concrete sidewalk showed very different air contents, loss of air at the surface, and most importantly, very low amounts of entrained air in the scaled panel (in red in (b)). Note: 1 in. = 25.4 mm

low air contents should have been rejected during placement—this indicates the importance of frequent air measurements during concrete placement. Even the ones having total air within the design requirements scaled due to their poor air-void systems—this indicates that fulfilling the design total air requirement does not necessarily guarantee frost resistance unless the concrete has a good air-void system. This indicates the importance of measuring not only the "total air" by conventional methods but also the air-void system (void amount, size, distribution, and spacing) during concrete placement. A recently developed instrument called "air-void

TABLE 3:
AIR-VOID PARAMETER, *W/CM*, AND CHLORIDE CONTENT OF SOUND AND SCALED CONCRETE CORES IN THE THREE CASE STUDIES DESCRIBED IN THE ARTICLE. PARAMETERS RESPONSIBLE FOR SCALING ARE HIGHLIGHTED IN RED. IN ALL CASES, THE SCALED AND SOUND CORES CAME FROM ADJACENT PANELS OR SIDEWALKS AND WERE EXPOSED TO SIMILAR ENVIRONMENTAL AND DEICING CONDITIONS

Case studies of scaling	Surface conditions of samples	Locations where various parameters were measured	Total air content , %	Entrained air content, %	Specific surface, in.^{2}/in.^{3}	Void-spacing factor, in.	Estimated *w/cm*	Chloride content, % by mass of concrete
Industry* recommended parameters	—	—	6 to 7 ± (1.5)†	—	≥ 600	≤0.008	≤0.45	—
Scaling due to poor air-void system of concrete								
I: Scaling due to nonair-entrainment	Sound	Top 1/8 to 1/4 in.	4.4	3.0	920	0.007	0.50	0.212
		Interior	4.8	4.0	635	0.007	0.48	0.024
	Scaled	Top 1/8 to 1/4 in.	1.3	0.0	180	0.094	0.50	0.200
		Interior	2.0	0.0	155	0.280	0.46	0.014
II: Scaling due to improper air entrainment (coarse air-void system, large void spacing factor)	Sound	Top 1/8 to 1/4 in.	1.8	1.6	975	0.005	0.50	0.087
		Interior	5.8	4.8	685	0.007	0.45	0.004
	Scaled	Top 1/8 to 1/4 in.	0.9	0.5	350	0.025	0.50	0.076
		Interior	2.8	1.7	500	0.012	0.45	0.008
III: Scaling due to inadequate air entrainment (low amount of entrained air)	Sound	Top 1/8 to 1/4 in.	3.7	1.5	615	0.010	0.45	0.139
		Interior	8.5	3.0	350	0.009	0.40	0.023
	Scaled	Top 1/8 to 1/4 in.	3.2	0.3	270	0.024	0.45	0.111
		Interior	4.5	0.5	170	0.033	0.40	0.012

*ACI 201.2R-01, "Durability of Concrete"; ACI 212.3R-91, "Chemical Admixtures for Concrete"; ACI 318-02/318R-02, "Building Code Requirements for Structural Concrete and Commentary"; ASTM C 457, and the like.

† The industry-recommended air content is for concrete containing 1/2 to 1 in. (13 to 25 mm) size aggregates and exposed to severe weather condition.

Note: 1 in. = 25.4 mm; 1 mm^2/mm^3 = 25.4 in.^{2}/in.^{3}

analyzer" has the potential to measure void size and spacing in fresh concrete. Widespread applications of such instruments are essential for assuring a good air-void system in fresh concrete.

SALT CAUSING SCALING

Due to the lower vapor pressure of salt solution than water at a given temperature, deicing salts increase the degree of saturation of concrete, keep concrete saturated during the drying stages, and increase the number of freezing-and-thawing cycles. Unless the concrete is dense enough to prevent the salt-induced saturation; is mature; and has a good air-void system of adequate, close-spaced, fine entrained air voids to protect the paste, the concrete will always be susceptible to scaling in the presence of salt. Deicing salts can cause and aggravate scaling in nonair-entrained or inadequately air-entrained concrete. The previous three case studies show that having a good air-void system is very important in maintaining a quality concrete in the deicing exposures. Exposure to salt prior to the attainment of maturity, however, can cause scaling even in properly air-entrained concrete. A magnesium chloride-based deicer can cause a chemical attack even in a properly air-entrained concrete and soften the surface by forming magnesium hydroxide (brucite) and decomposing the calcium-silicate-hydrate component of portland cement hydration (the main cementitious component of concrete) into a soft, friable product called magnesium-silicate-hydrate. Deicers containing ammonium sulfate or ammonium nitrate also attack the cement paste and should be avoided.

SALT VERSUS GOOD QUALITY CONCRETE

To return to the question in the title, salt should not cause scaling if the concrete is of good quality (that is, it has adequate entrained air, a good air-void system in the body and at the surface, and is made using well-graded, frost-resistant aggregates), properly constructed (that is, placed, finished, and cured), and mature prior to the first exposure to winter weather and salt. Due to the increased saturation of the concrete, salt not only increases the severity of scaling in an inadequately air-entrained concrete, but also in concrete that has a coarse air-void system. Over the years, many outdoor concrete slabs have performed well in harsh winter weathering and have been exposed to deicing salts without scaling because they were made using a good quality concrete, following good construction practices, and were protected from salts in the early stages before the attainment of maturity. In many places, salt may be needed for public safety and should not be blamed for scaling before verifying the quality of the concrete and the construction details. We cannot bypass the responsibility of providing a good, durable concrete before putting the blame on salt for scaling.

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