DELAMINATION – A STATE-OF-THE-ART REVIEW

Dipayan Jana

Construction Materials Consultants, Inc. and
Applied Petrographic Services, Inc., Greensburg, PA 15601 USA

ABSTRACT

One of the increasing problems in concrete slabs is **delamination**, which is a plane of "separation," usually forms within the top $^{1}/_{4}$ to 1 in. (6.25 to 25 mm) of the finished surface, and orients parallel to the surface. Delamination can occur by a variety of reasons, such as: (a) the use of air entrainment in a concrete slab receiving a hard trowel finish; (b) machine-trowel finishing a lightweight aggregate concrete slab; (c) premature finishing of a slab prior to the cessation of bleeding; (d) top-down stiffening, or surface crusting of a concrete slab in a hot, windy, or dry weather, especially in a concrete undergoing slow and prolonged bleeding; (e) prolonged finishing operations on an outdoor air-entrained concrete slab, or, on a slab receiving a mineral or metallic surface hardener; (f) corrosion of reinforcing steel in concrete in the presence of chlorides and/or atmospheric carbon dioxide; and (g) cyclic freezing and thawing of a non-air-entrained, or poorly air-entrained concrete slab at critically saturated conditions.

Methods of detecting the delaminated areas in a slab include: (a) metal tapping, (b) manual or automated chain dragging, (c) electro-mechanical sounding, (d) impact echo, (d) infrared thermography, and (e) ground penetrating radar.

Among the techniques available for diagnosing the causes of delamination, petrographic examinations, along with detailed air void analysis of concrete cores from the delaminated areas are determined to be the most effective. After explaining factors responsible for delamination, and the techniques available for quantitative measurements of delaminated areas, the present paper provides case-study-based examples of detailed investigations of various mechanisms of delamination by diagnosing the evidence present in the delaminated concrete slabs. Finally, a list of common industry recommendations is provided to avoid such an increasing nuisance in the modern concrete slabs.

Increasing occurrences of delamination in both indoor and outdoor concrete slabs are, unfortunately, the results of modern fast track construction schedules, where inadequate design or, failure to follow a design causes the failure, such as either by accidentally incorporating air in a slab that will not be exposed to freezing during its service and will receive a machine trowel, or not incorporating air in an outdoor slab that will be exposed to freezing.

INTRODUCTION

According to the ACI Committee 116 report on 'Cement and Concrete Terminology', **delamination** is defined as "a separation along a plane parallel to a surface as in the separation of a coating from a substrate or the layers of coating from each other, or in the case of a concrete slab, a horizontal splitting, cracking, or separation of a slab in a plane roughly parallel to, and generally near, the upper surface; found most frequently in bridge decks and caused by the corrosion of reinforcing steel or freezing and thawing; similar to spalling, scaling, or peeling except that delamination affects large areas and can often only be detected by tapping." [1]

Delamination is a nuisance to bridge decks, machine-trowel finished industrial floors, concrete pavements, sidewalks and other indoor and outdoor concrete slabs. In outdoor concrete slabs exposed to cyclic freezing and thawing and deicing chemicals, delamination represents a horizontal crack, or a series of cracks oriented parallel to the exposed surface, and extended to depths depending upon the depth of extension of the freezing front, or, to the depth of the corroded reinforcing steel in a concrete slab. In indoor concrete slabs, delamination usually represents a single, shallow, horizontal, near-surface separation, oriented parallel to the finished surface, and usually occurs at a depth of $^1/_4$ to $^3/_4$ in. (6.25 to 18.75 mm). Delamination usually refers to distress that affects areas larger than 6-in. (150 mm) in lateral dimension (Figure 1), from a few square inches to more than 100 sq. ft. [2], and occurs at a depth ranging from shallow ($^1/_{16}$ in. or 1.5 mm) to deep ($^3/_4$ in. or 20 mm, or, more in the outdoor slabs).

Over the last two decades, a number of publications appeared on the *factors* responsible for delamination [2-30] and on *detection* of delamination in the field by various non-destructive methods [32-38]. By contrast, relatively limited literature exists on the *methods of diagnosing* the factors responsible for causing the delamination. After giving a brief overview of the factors and the field detection methods, this article shall provide the importance of petrographic examinations in diagnosing the causes of delamination.

CAUSES OF DELAMINATION

In the ACI Committee 116's definition [1], corrosion of steel in concrete and cyclic freezing are mentioned as the two common causes of delamination. These are frequently the cases in bridge decks, parking garages, and other outdoor concrete slabs exposed to cyclic freezing and thawing, and deicing salts. In indoor floors, however, none of these are the common cause of delamination. In indoor slabs, delamination occurs by a variety of ways related to: (a) air entrainment and concrete materials; (b) timing, duration, and method of finishing; (c) weather and subgrade conditions during concrete placement; and (d) factors that affect bleeding rate, capacity, and duration.

Following are brief descriptions of some common factors, which, either individually, or in combination, can cause delamination:

(1) **Air Entrainment -** Incorporation of entrained air in an indoor concrete slab receiving a dense, hard, machine-troweled finish is known to be a common cause for delamination. The higher the air content, and/or the higher (and longer) the finishing pressures, the higher the potential for delamination [3-6].

The potential for delamination is high in the following cases:

- The total air content is higher than 3 percent. According to ACI Committee 301 and 302 reports [5, 6], a machine-trowel-finished, normal-weight concrete slab should not incorporate entrained air; and the total air content should not exceed 3 percent.
- Air entrainment is specified for a slab exposed to subfreezing temperature during the early stages of construction, but has subsequently been machine trowel-finished [7].
- Air entrainment is specified in a mixture for a particular section of a construction (e.g., outdoor loading dock of an indoor warehouse floor) but was mistakenly used everywhere and was machine-trowel-finished.
- Pressure applied to the surface during finishing is greater than that usually occurs during light floating or brooming (especially during troweling, early use of float pans, or early steepening of finishing blades) and has squeezed water and washed air out of the near-surface region at the early period of finishing.
- Air entrainment is specified in the mix design of a machine trowel finished lightweight concrete slab for unit weight requirements in lightweight concrete.

There are three ways air increases the potential for delamination:

- Compared to a non-air-entrained concrete, air-entrained concrete bleeds slowly, which increases the probability of initiation of finishing prior to the cessation of bleeding, especially if the slab is placed in hot, windy, or dry weather and is experiencing surface stiffening [9-12]. Finishing a crusted or stiffened surface while the air-entrained concrete is still bleeding causes entrapment of bleed water beneath the crusted/stiffened surface.
- Entrained air makes concrete sticky and cohesive, which can increase the difficulty in achieving an acceptable finish [6]. Prolonged finishing operations (especially in floors with high flatness and levelness requirements) remove air voids out of the surface, and create a dense, air-free (or low air) near-surface zone that shears against the underlying less dense, interior air-entrained concrete, and eventually results in a weak plane between the two.
- Prolonged trowel finishing operations of an air-entrained concrete squeeze water and wash air out of the densified near-surface zone, and accumulate them immediately beneath the densified surface to create the delamination. Also, prolonged finishing changes the shape of spherical voids into numerous elongated, discontinuous, stringy voids, or micro-separations (also called incipient delamination), the coalescence of which can eventually create a large-scale separation, or delamination.

(2) **Premature Finishing -** Initiation of finishing prior to the cessation of bleeding and initial set of concrete usually causes entrapment of bleed water beneath the densified finished surface through which water cannot pass. The accumulated water beneath the near-surface zone creates an internal, high water-cementitious materials ratio (hereafter *w/c*), near-surface plane of weakness, which is susceptible to delamination by traffic load, or by cyclic freezing of the trapped water [6, 11-14, 16, 17].

Factors that cause premature finishing of a concrete slab include:

- The presence of entrained air, fine particulates such as pozzolans, too much fines in sand, set-retarding chemicals, a combination of these, and all other factors, which slow down bleeding;

- Rapid evaporation of surface water and disappearance of bleed water sheen from the surface, which calls for initiation of finishing while the concrete may be bleeding inside.
- Early use of float pan, walk-behind or ride-on power trowel, while the concrete inside is still bleeding [18-23].

(3) **Prolonged Finishing** – According to ACI Committee 308R-01 report on curing, the "window of finishing" is defined as the time between the initial and final sets of concrete (Figure 2, [6, 15]). Finishing operations that extend beyond the final set, especially in floors with high flatness and levelness requirements, or, in floors having metallic or mineral surface hardener increases the potential for delamination (especially if the process of installation of surface hardener deviates from that of the manufacturers' recommendations). Also, as mentioned before, entrained air tends to extend the duration of finishing due to the sticky nature of the air-entrained concrete. Prolonged finishing operations wash air and squeeze water out of the surface, which may accumulate immediately beneath the dense, low *w/c* near-surface zone (usually $^1/_8$ to $^3/_4$ in. thick) and creates a plane of weakness. Prolonged finishing is indicated by the thickness of this near-surface low (or no) air, low *w/c* densified zone. Unlike premature finishing, which causes entrapment of bleed water beneath the finished surface, prolonged finishing can accumulate both the squeezed water and the air from the near-surface densified region to below it to cause the delamination.

(4) **Surface Crusting (Top-Down Stiffening) -** Rapid top-down stiffening of a slab on a hot, windy, sunny, and dry day prior to the cessation of bleeding creates a stiffened, "crusty" surface without any bleed water sheen (common in fall and spring, [21]) – this calls for the initiation of finishing while the concrete may still be bleeding inside. Bleed water accumulates beneath the crusted surface and eventually creates a plane of delamination. This occurs when the rate of evaporation of surface water is higher than the rate of bleeding [6, 21], which can also cause crazing and plastic shrinkage cracking. Beside the weather condition (high wind, hot air, low relative humidity, direct sun), top-down stiffening can also occur when a slab is too thick with big temperature-moisture differentials between the top and bottom surfaces, or, when the slab is placed on a cold, non-absorptive subbase, which prolongs setting of concrete at the bottom compared to that at the top [21, 28].

(5) **Bleeding & Setting -** Factors that reduce bleeding rate, increase bleeding capacity, and extend bleeding duration and initial set are susceptible to increase the potential for delamination [24, 25]. Such factors are: (a) placement of a slab on a cold, non-absorptive subbase (which increases bleeding capacity and duration [27]); (b) high air temperature (which decreases the time of setting, bleeding rate and duration [24]); (c) high wind speed (which increases the rate of evaporation of bleed water); (d) thick slab (which increases bleeding capacity); (e) the presence of entrained air, mineral admixtures finer than portland cement, excessive fines in sand, other fine particulates, low water and/or high cement content in concrete (which decrease bleeding rate and capacity but usually do not affect duration or setting, [17]); and (f) use of set-retarding chemicals especially in cold weather (which retard setting and prolong bleeding, [17]). These factors, in combination with the ones that cause top-down stiffening, greatly increase the potential for delamination.

(6) **Cyclic Freezing and Thawing** – One of the common causes of delamination of bridge decks is cyclic freezing and thawing of non-air-entrained or poorly air-entrained concrete

at critically water-saturated conditions, which creates many horizontal, surface-parallel cracks that transect and circumscribe the aggregate particles, extend to depths of freezing fronts, and define several planes of delamination. Unlike trowel-finished indoor slabs, where air entrainment is the common cause of delamination, in outdoor slabs exposed to freezing and deicing chemicals, air entrainment is the remedy to the delamination. Unlike a single plane of delamination at a very shallow depth in the near-surface region in an indoor slab, delamination by cyclic freezing of outdoor slab can occur in many planes and through the entire depth depending on the severity of winter and the level of water-saturation of concrete.

(7) **Corrosion of Steel in Concrete** – Corrosion of steel in concrete is another common reason for delamination of bridge decks and parking garage slabs, especially when the concrete is exposed to chloride-containing deicing salts [1, 31, 36]. Penetration of chloride, oxygen, and moisture to reinforcing steel in concrete causes *chloride-induced corrosion* of steel, which starts in the form of pitting-type corrosion on the steel surface. Penetration of carbon dioxide and subsequent carbonation of cement paste causes a reduction in alkalinity of pore solution, destabilization of the oxide film around the reinforcing steel, and *carbonation-induced corrosion* of steel in concrete. Corrosion of steel causes a loss of bond between the steel and the adjacent concrete, and, subsequent cracking and spalling of the concrete cover above the corroded steel. Formation of corrosion products is associated with a significant increase in volume, which is the main reason for the cracking and spalling of concrete over the corroded steel. Initial microcracking and local spalling of concrete promote further entry of corrosive agents into concrete and down to the steel for further corrosion (corrosion-cracking-corrosion cycle). Corrosion of many adjacent reinforcing bars causes a large-scale spalling or delamination [31]. The thickness and the quality of the concrete cover (i.e., durability and impermeability of concrete cover to the external agents of corrosion, crack resistance) over the reinforcing steel control the onset of corrosion and delamination. A dense, impermeable, well-cured, well-consolidated, low *w/c*, crack resistant concrete cover having a thickness of at least an inch is usually recommended for the protection of steel from corrosion and from corrosion-induced delamination.

(8) **Improper Installation of Surface Hardener, Sealer, Coating, Membrane, or Floor Covering** – Hardener, sealer, coating, waterproofing membrane, or floor covering installed on an improperly prepared concrete substrate surface, without following the manufacturers' recommendations, or, installed "early" on a slab with a high moisture-vapor emission rate can lead to bond failure and debonding [6, 16, 29, 30]. Differential volume changes between the sealer/coat/cover and the concrete substrate due to differential thermal and/or moisture conditions can also cause de-bonding. Trapped moisture between the multiple coats of sealer or between sealer and concrete can cause sealer or coating failure [30]. These types of failure, though fall under the ACI definition of 'delamination', are actually different from the ones described before, which occur within or near the surface region of concrete.

<u>In Summary</u> – Conditions that can cause delamination include:

(1) Air-entrainment in a concrete slab receiving a hard (machine)-trowel finish (especially in an indoor slab where air entrainment is not necessary);
(2) Machine trowel finishing operations on a lightweight aggregate concrete slab, which usually incorporates air entrainment;

(3) Premature finishing operations of an air-entrained or non-air-entrained concrete slab in indoor or outdoor environment;
(4) Top-down stiffening, or surface crusting of a concrete slab in hot, windy, and/or dry weather, especially if the slab is experiencing slow and prolonged bleeding;
(5) Prolonged finishing operations on an outdoor air-entrained concrete slab, (especially if the air content is higher than 3 percent);
(6) Prolonged finishing operations on a concrete slab receiving a metallic or mineral surface hardener;
(7) Corrosion of reinforcing steel in concrete in the presence of chloride and/or atmospheric carbonation; and,
(8) Cyclic freezing and thawing of a non-air-entrained or poorly air-entrained concrete slab at critically saturated conditions.

DETECTING DELAMINATION

Since delamination represents a ‘separation’ between the surface and the body of the concrete, or a series of fracture planes in concrete, it can be detected by any nondestructive method that detects internal voids, gaps, and cracks in concrete. Manning and Holt [33], ASTM D 4580 [32], ASTM D 4788 [34], Khan [35], ACI Committee 222R report [36], ASTM C 1383 [37], and ASTM D 6087 [38] provide excellent description of many of these methods. The methods are briefly described in the following paragraphs:

(1) **Metal Tapping** – Tapping the surface with a metal rod, or a lightweight hammer emits a dull, hollow sound from the delaminated areas and a sharp, ringing tone from the sound areas [33, 36]. On vertical and overhead concrete surfaces tapping by a hand-held hammer or a long steel rod can easily detect the delaminated areas.

(2) **Chain Dragging** – Dragging a heavy logging chain across the floor with a whip-like action also creates a similar hollow resonance from the delaminated areas. The method is standardized in ASTM D 4580 [32] and in Manning and Holt [33]. The device consists of 4 or 5 segments of 1-in. (25 mm) link chain of $^1/_2$ in. (6mm) diameter steel, approximately 18 in. (45.7 cm) long, attached to a 2-ft. (61 cm) piece of aluminum or copper tube to which a 2 to 3 ft. (61-91.4 cm) piece of tubing, for the handle, is attached to the midpoint, forming a T [32]. Khan [35] mentions an automated chain-drag system for covering a large area.

(3) **Electro-Mechanical Sounding** – In this method [ASTM D 4580; 32, 33, 35] a calibrated, small, three-wheeled cart sounding device is pushed along a series of parallel, longitudinal lines drawn at predetermined spacing on the surface – two electrically powered rigid-steel-tapping wheels (capable of tapping the surface at the rate of 33 times/sec) located approximately 6 in. (152 mm) apart, emit vibrations into the surface that are sensed by two sonic receiving wheels located 3 in. (76 mm) outside of, and parallel to their corresponding tapping wheels. Delaminated areas are indicated by deflections or waves on a two-channel-strip chart recorder that is capable of receiving the signals from the sonic receivers [32, 33]. The device can detect delaminations up to 2.6 in. (65 mm) below the surface of slab [33].

(4) **Infrared Thermography** – The method is described in ASTM D 4788 [34], Manning and Holt [33], and Khan [35]. It is based upon the principle that when a thermal front moves through a concrete, delamination or gaps create a localized temperature discontinuity to become detectable on the surface. Delaminated is detected by the

difference in surface temperature between the delaminated and the underlying sound concrete under certain atmospheric conditions. This method can be used from both the ground and the air and is best during periods of rapid heating and cooling when the temperature differentials are high.

(5) **Impact-Echo** – Impact echo method is based upon the relation between the travel-time of a wave through a given section of concrete and the wave-velocity [Depth of delamination = P-wave velocity /(2 $\times$ frequency); the wave-velocity is determined by impact echo of a sound slab of a known thickness]. A small steel impactor emits mechanical energy in the form of stress (P) wave into concrete - the wave travels to and reflects back from a delaminated surface, and is received by a transducer mounted on the surface and close to the impact point. The collected signals are processed in a computer and converted into frequency graphs for evaluation. ASTM C 1383 [37] describes this method to determine the thickness of an in-place concrete slab.

(6) **Ground-Penetrating Radar (GPR)** – GPR emits electromagnetic energy in the form of radio frequency pulses into the concrete – the energy reflects back from a delaminated surface (which is the interface between materials with different dielectric or conductive characteristics), and is received by a radar antenna. ASTM C 6087 [38] describes use of GPR to detect delamination.

The method to choose in a particular situation depends upon the simplicity, the area to be covered, the cost of operation, the time involved, and the level of accuracy desired. Among these techniques, metal tapping and chain dragging are more commonly used than the others, especially during investigation of delamination in a localized area (e.g., a parking structure or a warehouse floor). Impact echo is useful for detecting delamination in a small area (e.g., in a concrete core). Infrared thermography is useful in a laboratory sample (where the sample can be heated prior to testing), or in the field during a bright sunny day (i.e., with large temperature variations) on a clean surface free from debris. Unlike all these methods (which cannot detect internal flaws situated beneath the first layer of delamination), GPR can detect multiple layers of flaws over the entire thickness of a concrete member; with further technological advances and adequate training GPR can be used successfully for detecting delamination over many large structures, such as bridge decks.

DIAGNOSING CAUSES OF DELAMINATION

Petrographic Examinations

Based upon the detection and aerial extend (mapping) of delamination, core or saw-cut sections are usually taken from the delaminated and sound areas for diagnosing the causes of delamination. Petrographic examination, following the guidelines of ASTM C 856-02 [39], is the most common and reliable method for diagnosing the cause(s) of delamination.

The following excerpts from the ACI Committee 302 report [6] on analysis of surface imperfections describe the importance of petrographic examination:

> "The cause of most surface imperfections can be determined by petrographic (microscopic) analysis on samples of the concrete. A petrographic analysis of concrete is performed in accordance with ASTM C 856.

> Samples for the analysis are usually 4-in. diameter (100-mm) drilled cores or saw-cut sections. Broken sections can be used, but cores or saw-cut sections are preferred because they are less apt to be disturbed. Samples should represent concrete from both the problem and the non-problem areas. The petrographer should be provided with a description and photographs of the problem, in addition to information on the concrete mixture proportions, construction practices used, and environmental conditions. A field review by a petrographer, engineer, or concrete technologist is also helpful in analyzing the imperfection.
>
> The petrographic report often includes the probable cause of the problem, extent of distress, the general quality of the concrete, and expected durability and performance of the concrete. Corrective action, if necessary, would be based to a great extent on the petrographic report."

Petrographic examinations include detailed investigation of various physical, textural, mineralogical, and compositional properties of concrete at the surface, in the near-surface region, at the delamination plane, and in the body of the concrete. Some of these properties include:

- Color, texture, hardness, density, water-absorption, and condition of the finished surface.
- Characteristics of dry shake metallic, or mineral surface hardener - thickness of individual coats, total thickness; separations between the coats in hardener, between the hardener and the concrete, or within the concrete near the concrete-hardener interface.
- Color, texture, hardness, density, *w/c*, air content, paste content, types of voids, degree of cement hydration in the near-surface region of slab down to a depth of $^{3}/_{4}$ to 1 in. [(18-25mm) above the plane of delamination]; and, variations of these properties between the near-surface region and the interior of the slab.
- Depth-wise variation of air content and other air-void parameters [40] (air-profile), and *w/c*.
- The depth, width, and extend of delamination; whether it occurs as a single continuous plane, or as several uneven, discontinuous but more or less parallel planes through a certain depth, the texture and appearance of the delaminated surfaces (which constitute the underside of the delaminated piece having the finished surface and the top side of the exposed delaminated surface of the slab).
- The presence of any "incipient delamination", which is a discontinuous separation, loosely holding the finished surface to the body that can eventually form a larger separation, or delamination.
- Short, discontinuous, elongated, "micro-separations" within the paste and/or along aggregate-paste interfaces, and distorted (elongated) 'stringy' air-voids oriented parallel to the finished surface that usually forms in the semi-plastic state due to the finishing manipulations.
- Evidence of excessive bleeding (progressively increasing *w/c* towards the top, except at the very top dense near-surface region; settlement of coarse aggregate particles); evidence of bleed water entrapment underneath the finished surface (e.g., the presence of high *w/c* and high air zone associated with delamination and situated underneath the dense surface mortar, the presence of elongated or distorted former bleed water voids at the underside of delaminated piece, on the exposed delaminated surface, or under the dense near-surface mortar; vertical bleed water channels intersected by the delamination plane or dense surface mortar).

- Evidence that affect bleeding rate, capacity and duration; evidence of rapid evaporation of surface water and premature stiffening of surface. Thickness of slab from the core sample, subbase conditions, cracks patterns (if any).
- Evidence of corrosion of reinforcing steel in concrete.
- Evidence of delamination due to cyclic freezing of poorly air-entrained or non-air-entrained concrete, or concrete having a high *w/c*, improper finishing, poor curing, or poor drainage, etc.

(1) Delamination in a Machine-Trowel Finished, Indoor, Air-Entrained Concrete Slab

Petrographic examinations often identify four characteristic features in a machine-troweled air-entrained concrete slab (see Figures 3, 5, 6, and 7).

(a) The first feature is the significant decrease in air content from the interior towards the finished (or, delaminated) surface [particularly at the top $^1/_2$ to $1^1/_2$ in. (12.5-37 mm)], which eventually reduces to essentially no or very low air at and immediately beneath the finished surface. Figure 3 shows a lapped cross-section of a core from a hollow-sounded area in a delaminated slab and an air profile of the core, determined by the modified point count method of ASTM C 457 on the lapped cross section, as shown in a diagram in Figure 4[40]. The profile shows a dramatic decrease of air at the top $^1/_2$ in. due to machine-troweling. Paste content shows an increase, which is associated with the deep embedding of coarse aggregate particles by finishing manipulations.

(b) The second feature is the plane of delamination (Figures 3, 5, 6, and 7). To a depth of $^1/_8$ to $^3/_4$ in. (3 to 18 mm) from the finished surface occurs a long, continuous separation of width varying from $^1/_{32}$ to $^1/_{16}$ in. (<1 to 1.5 mm) that orients parallel to the finished surface, circumscribes the aggregate particles, and defines the plane of delamination. Many core samples from delaminated slabs do not always show a single continuous separation but, instead, have several discontinuous, elongated separations at similar depths that define ‘incipient delamination’. Associated with, and situated immediately above and below the delaminations is a zone of small, elongated, irregularly shaped entrapped air voids or ‘micro-separations’ that orient parallel to the delamination (Figures 3, 5, and 6). Many of these voids adhere to the topside or underside of coarse aggregate particles.

(c) The third feature is the contrasting characteristics of the near-surface zone situated above the delamination and the rest of the body of the slab. The near-surface mortar [usually extents to a depth of $^1/_8$ to $^1/_2$ in.(3 to 12.5 mm)] is denser, harder and darker than the interior concrete; paste in this region is very dense, dark, hard, and contains abundant residual portland cement particles, which is significantly higher than that present in the body (Figure 6) – this is due to the lower *w/c* of this densified near-surface zone compared to the *w/c* in the body. Such variations are indicative of machine-troweling operations that squeeze water and wash air out of the surface.

(d) The forth feature is the texture and properties of the undersides of delaminated pieces and the mated exposed delaminated surface in the slab. The surfaces that define the delamination often contain elongated or irregularly shaped short discontinuous voids, abundant aggregate sockets due to weak aggregate-paste bonds, soft paste that are indicative of entrapment of bleed water and intersecting bleed water channels by the densified surface. Sometimes paste in this region appears softer and have a higher *w/c* than the paste at the top (in the near-surface zone), or in the body – this is due to the presence of entrapped bleed water, which has caused the delamination.

In an article [41] entitled "Air Entrainment and Detecting Delaminations" David R. Lankard mentioned distinct microstructural zones in a delaminated concrete slab, which are consistent with the above description, and are shown in Figure 7. Figure 7 shows examples, from six different case studies, where the delamination plane and other microstructural features are distinct on lapped cross-sections of cores taken from delaminated slabs. In all cases, machine troweling operations on air-entrained concrete slabs have created the following features:

(a) A dense, dark, hard, low water-cement ratio (*w/c*), low (to literally no) air surface zone, extended to a depth of $^{1}/_{8}$ to $^{1}/_{4}$ in. (3 to 6.25 mm) that is enriched in mortar fraction and low in coarse aggregate fraction – this layer is mentioned as the "densified surface layer" or "DSL" by Lankard);
(b) A transitional zone of gradually decreasing air and increasing paste content from the interior toward the surface; the zone has a depth-wise variation of air content, which is higher than the air in the DSL but lower than the air in the interior concrete, and a *w/c* similar to that in the interior trowel-unaffected concrete. This transitional zone is described by Lankard as the "distorted layer" or "DT". It extends to a depth of $^{3}/_{4}$ to 1 in. (18 to 25 mm), and contains the following characteristic microstructural features – (i) irregularly-shaped or distorted air voids, (ii) elongated or stringy voids; (iii) tears or short, discontinuous separations in the paste; (iv) aggregate-paste bond distortions; and (v) very steep air and paste profiles;
(c) The plane of delamination, occurring as a long, continuous, near-horizontal surface-parallel separation between the trowel-affected DSL plus DT zone and the trowel-unaffected interior concrete that stays within the top 1 in. (25 mm) of the surface, and is less than $^{1}/_{4}$ in (6 mm) width; and, finally,
(d) The trowel-unaffected interior concrete with more or less uniform air, paste and *w/c* profiles (Lankard's "as placed concrete" or "APC").

Features "a" through "c" are the physical consequences of the finishing manipulations on an air-entrained slab that has been machine-troweled. All these features are the end results of the physical actions of troweling, which eventually cause the delamination. These physical effects of troweling, however, are completely independent from delamination caused solely by the entrapment of bleed water beneath a trowel-densified surface. Bleed water entrapment can occur in both air-entrained and non-air-entrained slabs by: (a) early finishing-induced surface densification prior to the cessation of bleeding and (b) surface crusting or top-down stiffening prior to the cessation of bleeding – both can cause delamination in a slab even without hard-trowel finishing. It is also not uncommon to see that both mechanisms (i.e., troweling-induced formation of DSL, DT, and delamination, as well as bleed water entrapment beneath the delaminated surface) have aggravated the situation. Entrained air by itself can indirectly influence bleed water entrapment (and delamination) due to premature finishing prior to the cessation of bleeding by reducing the bleeding rate, and/or by prolonged finishing (air makes concrete sticky). It is, however, more of the physical action of troweling itself on an air-entrained concrete that has more influence in causing the delamination than the inherent effects of air in concrete.

The question, however, is exactly how the plane of delamination forms in a plastic concrete. Based on the above-mentioned microstructural features, various scenarios can be proposed, which can create the plane of delamination:

(a) The first one is the physical action of troweling that causes shearing and repeated pulling actions (the "chewing gum" effect) between the densified, stiffened, no-air surface region and the less-dense and less stiffened interior concrete of differential rheologies causing the development of a weak zone (eventually leading to delamination) between the two. The earlier the troweling starts (i.e., immediately after the initial set of concrete, or during early applications of pan floats) and the higher the troweling pressure, the higher the possibility of the shearing/pulling actions on plastic concrete and hence the delamination. Delamination by the physical force of troweling is more prevalent in an air-entrained slab than in a non-air-entrained slab because the stiffness differential between the surface and the interior is higher in the former.

(b) The second scenario is the coalescence of elongated or stringy voids and the tears in the DT to form the delamination. The problem with this scenario, however, is the significant differences in scales and numbers of elongated voids or tears on the one hand (which are very fine, short, recognized mostly under optical microscopes, and numerous) and the plane of delamination itself on the other (which occurs in macro-scale, commonly as one single plane, and continuous). Formation of the plane of delamination by the coalescence of elongated voids and tears should create more long planes of separations parallel to the main plane of delamination than just one single plane at the base of the DT that defines an abrupt change in the air profile of the slab. The author has seen cases where delamination did not necessarily occur beneath the DT layer, but within or even above that (beneath the DSL layer) especially where a metallic or mineral surface hardener was used. In a slab with a surface hardener, the DT layer may not occur – the hardened surface probably reduces the shearing/pulling action and void distortion in the DT layer.

(c) The third scenario is the formation of delamination by the accumulation of air voids from the trowel-affected surface region (i.e., from both DSL and DT) down beneath it. Air voids follow the Boyle's law, which is the principle for air measurement in plastic concrete by the conventional pressure meter. If troweling pressure compresses air at the surface region, after the pass of the troweling machine, when the pressure releases, the surface should regain some of its lost air (unless the surface sets too fast) – but the surface region invariably shows almost no air, which indicates a probable "washing" of surface air (by repeated applications of troweling pressures) down beneath the trowel-affected zone as the eventual plane of delamination.

(d) The first three scenarios indicate the physical actions of troweling itself in causing the delamination. The fourth scenario involves air-induced reduction in the bleeding rate and a tendency for initiation of finishing (e.g., early applications of pan floats) while the concrete may still bleed internally. Subsequently, bleed water is entrapped beneath the finished surface (this can also be accentuated by surface crusting or top-down stiffening by the environmental influence on concrete). This scenario may or may not form the tears, elongated voids, aggregate-paste bond distortions, and the typical air profile, which are the consequences of the physical actions of finishing.

(e) The fifth scenario involves increased difficulty in finishing an air-entrained slab rather than a non-air-entrained slab (air makes concrete "sticky"), which may increase the pressure and/or the duration of finishing, formation of a thickened zone of DSL and DT, and hence, an increased potential for delamination.

The delamination, incipient delamination and micro-separations are, therefore, the result of trowel-finishing operations on an air-entrained concrete. Hard, machine-troweling is necessary in industrial floors, especially for slabs with stringent flatness and levelness requirements, but air entrainment is not necessary for many such "indoor" floors [3]. Air undoubtedly increases the potential for delamination by forming elongated micro-separations that eventually form the delamination, by accumulating beneath the dense surface, or by slowing down the bleeding, which in turn, increases the potential for entrapment of bleed water underneath the finished surface.

(2) Delamination in a Lightweight Aggregate Concrete Slab

ACI Committee reports 301 [5] and 302 [6] mention not to use air-entrainment in normal weight concrete slab that will receive a machine-trowel finish. Lightweight concrete, however, commonly incorporates entrained air for unit weight requirements. Machine troweling a lightweight concrete slab, therefore, increases the potential for delamination. Figure 8 shows such an example in a core from a delaminated lightweight concrete slab and significant reduction in air content at the top $^1/_2$ in. (12.5 mm). Figure 9 shows the profiles of air-void parameters, which show a significant decrease of air content, increase of paste content and increase of specific surface and void-spacing factor at the top $^1/_2$ in. (12.5 mm) section – such variations are indicative of reduction in size and abundance of near-surface coarser air voids by trowel-finishing. The extent of this reduced-air-zone is indicative of the pressure applied and the duration of finishing – thick, no-air zone indicates prolonged finishing. Delamination is due to entrapment of bleed water beneath the densified surface. Due to air entrainment, care should be taken in the time of initiation and the duration of finishing a lightweight concrete slab. Figure 10 shows an example of how high air can increase the potential for delamination.

(3) Delamination in a Prematurely-Finished Indoor or Outdoor Concrete Slab

Delamination, by premature finishing operations can occur either in a broom-finished outdoor slab, or in a trowel-finished indoor slab, irrespective of the presence or absence of entrained air, as long as finishing initiates before the cessation of bleeding. Figure 11 shows a core from a scaled sidewalk, where large areas having lateral dimensions of 6 to 8 in. (150 to 200 mm) have 'sheet-type scaling', which are characterized by large sheet-like masses of finished surface, having a nominal thickness of $^1/_8$ in. (3 mm) loosely adhered to the main body of the slab with a distinct gap. This gap between the loosely adhered incipient sheet-scale and the main body of the slab is indicative of entrapment of bleed water underneath the finished surface. Within the top $^1/_8$-in. (3 mm), paste is very soft, porous, fragile, dusty, water-absorptive, and earthy lustered, indicating the presence of excess water during finishing. On the underside of sheet-type scales are several coarse aggregate impressions or sockets where the paste is soft. The texture and appearance of the underside is indicative of the former accumulation of water underneath the scales; the scales are uniform in thickness from edge-to-edge. Other petrographic evidence are progressively increasing *w/c* towards the top, bleed water voids under coarse aggregate particles and vertical bleed water channels (Figure 11) – these features are present in the body, below the near-surface densified zone. Factors that extend bleeding duration, increase bleeding capacity, and reduce bleeding rate are also the evidence to suspect delamination by premature finishing. Figure 12 shows schematic diagrams of mechanisms of delamination by premature finishing of air-entrained and non-air-entrained slabs.

(4) Delamination in a Surface-Crusted (Prematurely and Rapidly Stiffened) Concrete Slab

The hot, sunny, dry, or windy weather condition during placement is the most important evidence for suspecting delamination by top-down stiffening and rapid evaporation of surface water at a rate faster than the rate of bleeding. Surface crusting is the result of such environmental impact on concrete, especially when curing is inadequate or absent to reduce the evaporation. Finishing a crusted surface can cause delamination if the internal concrete continues to bleed. According to ACI Committee 308 on curing [15], in such condition an initial curing should be provided before the initiation of finishing (Figure 2). Petrographic examination can sometimes detect evidence of, or lack of such intermediate curing. The examination usually detects soft, fragile (sometimes dusty), porous paste at the crusted surface, which contains abundant residual and relict portland cement particles having a very low degree of hydration (compared to the cement in the interior of the slab), and, shrinkage microcracks. A thicker-than-designed slab placed directly on a vapor retarder and containing a set retarder creates an added problem of extended period of bleeding and a high probability of entrapment of bleed water underneath the stiffened surface. In such cases, upward increase of *w/c*, narrow vertical or diagonal bleed water channels, and bleed water voids under the coarse aggregate particles indicate excessive bleeding.

(5) Delamination Due to Prolonged Finishing Operations of a Concrete Slab Receiving a Dry Shake Mineral or Metallic Hardener

Figure 13 shows a lapped cross section of a concrete core from a delaminated, industrial concrete floor, which has received a thin [less than $^1/_4$ in. (6 mm)] layer of metallic surface hardener (dry shake) to improve the abrasion and wear resistance. Prolonged finishing operations (beyond what was needed to incorporate and embed the hardeners into the surface), probably to achieve the anticipated floor flatness, has caused an eventual development of a plane of separation between the near-surface trowel-affected zone (i.e., the portion above the plane of delamination) and the interior concrete. Improper placement of hardener or improper finishing manipulation of a floor having a surface hardener can cause delamination of the hardener from the concrete, or a trowel-affected zone of concrete (including the hardener) from the interior concrete. Petrographic examinations usually diagnose the thickness of the surface hardener zone, its bond to the concrete, and the causes of delaminations.

(6) Delamination Due to Corrosion of Reinforcing Steel in Concrete

Figure 14 shows side view of a concrete core from a bridge deck where the concrete cover, i.e., the portion situated above the top layer of reinforcing bar, has been delaminated from the rest due to corrosion of reinforcing steel in concrete. The bar was extensively corroded on the surface, lost a portion of its cross-sectional area, and reddish-brown iron oxide corrosion product has been infiltrated into the neighboring areas. Expansion associated with corrosion of steel has weakened the steel-concrete interface, created spalls on small-scale such as the one in the core, and delamination on large scale in the field. Figure 14 also shows a schematic diagram of how isolated spalling from over the corroded reinforcing steel can eventually form a large-scale delamination. Figure 15 shows migration of corrosion products into paste from a corroded wire mesh. Examinations of lapped section in stereomicroscope, thin-section in petrographic microscope and polished section in scanning electron microscope are very helpful to determine the extent, morphology and composition of the corrosion products. In this example the corrosion product is identified as zinc chloride from the corrosion of a galvanized mesh.

Since corrosion of steel occurs either by carbonation of concrete associated with steel, and/or, by penetration of chloride to the depth of the steel, petrography and chloride analysis are the two common methods to determine the depth of carbonation of concrete and the chloride profile, respectively. Depth of carbonation is determined either by treatment of a freshly fractured surface of concrete with phenolphthalein alcoholic solution, which turns non-carbonated concrete pink and carbonated zone colorless, or, by thin-section analyses, where carbonated zone appears bright yellow due to the presence of calcium carbonate. Acid-soluble chloride analysis of the concrete cover at a regular interval up to the depth of steel shows high chloride contents that exceed the industry-recommended threshold chloride limit (i.e., 0.20% by mass of cement) for initiation of corrosion of steel in a non-carbonated concrete in the presence of oxygen and moisture. Concrete in cold weather that contains chloride-containing set accelerating admixture and/or receives chloride-containing deicing chemicals is susceptible to cause corrosion of steel. Petrographic examination is very useful to determine the thickness and the quality of the concrete cover and assessment of its role in promoting (or preventing) corrosion of reinforcing steel in concrete. Petrography is also used to evaluate the affects of various pozzolans in densification of the cover and the concrete-steel interface.

(7) Delamination Due to Cyclic Freezing and Thawing of Concrete

Figure 16 shows cross-sections of concrete cores from bridge decks and parking garages that have been extensively delaminated by numerous, surface-parallel cracks formed as a result of distress due to cyclic freezing of non-air-entrained or poorly air-entrained concretes at critically water-saturated conditions. The cracks are highlighted by treatment of the section with a fluorescence dye mixed alcoholic solution and exposure to ultraviolet radiation, or, by blue-dye mixed epoxy impregnation. The cracks are commonly visible in unaided eye, without a microscope (macro cracks), characteristically transect and circumscribe the aggregate particles, orient parallel to the exposed surface, and extend through the depth of the freezing front. Impact echo and ground penetrating radar are the two common methods for large-scale detection of multiple planes of delaminations (cracking) in outdoor decks and slabs by cyclic freezing and thawing.

CONCLUSION

Delamination is a nuisance to a concrete slab. It is an intimate interplay of concrete materials, construction practices, and environmental conditions that determines the probability of delamination. Among the concrete ingredients, air entrainment is the most common factor to cause delamination in an indoor slab, or, to prevent it in an outdoor slab. The density, impermeability, and thickness of the concrete cover determine the onset of delamination by corrosion of steel in concrete. Factors that slow down bleeding, or extend bleeding duration are susceptible to cause delamination by entrapment of bleed water beneath the finished surface. A number of nondestructive methods are available for field detection and lateral extend of delamination. Petrographic examination is the most powerful method for diagnosing the causes of delamination.

Unfortunately, the problem of delamination is increasing. Good concrete materials, concreting practices, and an in-depth knowledge of the behavior and properties of concrete are vital to prevent this problem. Table 1 provides some common industry guidelines for minimizing delamination. During repair, the depth of removal of delaminated portions to expose the sound concrete should be determined primarily by petrographic examination of core samples or saw-cut sections.

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Table 1: Top 10 Tips to Prevent Delamination (these are some general guidelines; applicability of these tips to a specific project should be consulted with a fully qualified and experienced engineer for the work)

1. Do not use air entrainment in indoor concrete slabs that receive a machine-trowel finish.
2. Use air entrainment in outdoor concrete slabs exposed to cyclic freezing and deicing chemicals.
3. If air entrainment is necessary for freeze-thaw resistance, avoid power trowels for finishing the surface, rather use magnesium or aluminum made bull or hand float, and burlap-drag or broom finish [8-12].
4. Do not start finishing prior to the cessation of bleeding. Wait until the bleed water sheen disappears from the surface, indentation of boot on the surface is not greater than $^1/_4$-in. (6 mm), and the concrete has attained the initial set.
5. If the weather conditions cause surface crusting (hot, dry, windy, sunny), wait even longer to reduce any internal bleeding, then provide adequate curing of the surface prior to and in between the finishing operations following the procedures mentioned in ACI 308-01[15], such as: (i) fog spray, to increase the relative humidity of air adjacent to the slab, (ii) covering the surface with a plastic film or wet burlap to prevent moisture loss, (iii) application of a commercial liquid membrane-forming curing compound, or (iv) evaporation reducers. Follow the manufacturers recommendations. Use sunshades or windbreaks, if practical.
6. Control the factors that influence the bleeding rate, capacity, duration, and top-down stiffening, such as thicker-than-normal slab, concrete placement in a hot, dry, windy and sunny day; direct placement of slab on a cold, low-absorptive subgrade; use of set-retarding admixtures; or low slump, low *w/c* concrete, air entrainment; etc. Inadequate vibration or over-vibration of a sticky concrete containing too much fines in sand cause surface crusting [25].
7. Do not place concrete on a cold subgrade, wait until it is warm by the sun, or warm it using heated enclosures to minimize the temperature differential between the subgrade, concrete and air. Also control the temperature of concrete. Place concrete on a dry, granular base, above the vapor retarder, which absorbs mixing water, reduces bleeding capacity and duration, sets the surface fast, and allows floating to start earlier [24]. However, if it is beneficial to place the slab directly on a vapor retarder (i.e., to reduce the moisture vapor transmission rate), carefully control the bleeding rate, capacity and duration, and provide adequate surface curing to minimize any top-middle-bottom differentials of temperatures, moisture conditions or setting behaviors of concrete within the slab.
8. Prior to the placement of a sealer, coating, hardener, or membrane, thoroughly clean the surface, scarify it (if needed), and install the product according to the manufacturer's recommendation.
9. Provide a dense, near-impermeable, crack-free, good quality concrete cover of adequate thickness over the reinforcing bars (preferably epoxy-coated) to combat corrosion and corrosion-induced delamination in bridge decks and parking garages.
10. Get adequate training of the construction procedures and the effects of environment on behavior and properties of concrete. Consult with experienced engineers and remember the common industry warnings. Follow the manufacturers' recommendations, and, various guidelines of construction practices in the *ACI Manual of Concrete Practice*.

Figure 1: An indoor machine-trowel-finished concrete slab showing delamination and loss of the finished surface from over a large area. Delamination refers to distress that affects areas larger than 150 mm (6-in.) in lateral dimension, from a few square inches to more than 100 sq. ft.[2], and occurs at a depth ranging from shallow ($^1/_{16}$-in. or 1.5 mm) to deep ($^3/_4$ in. or 20 mm, or, more in the outdoor slabs). Delamination was due to the use of air entrainment in this concrete slab, which has received a hard trowel finish. Photo curtsey of Concrete Construction Image Library Volume 1 of Portland Cement Association.

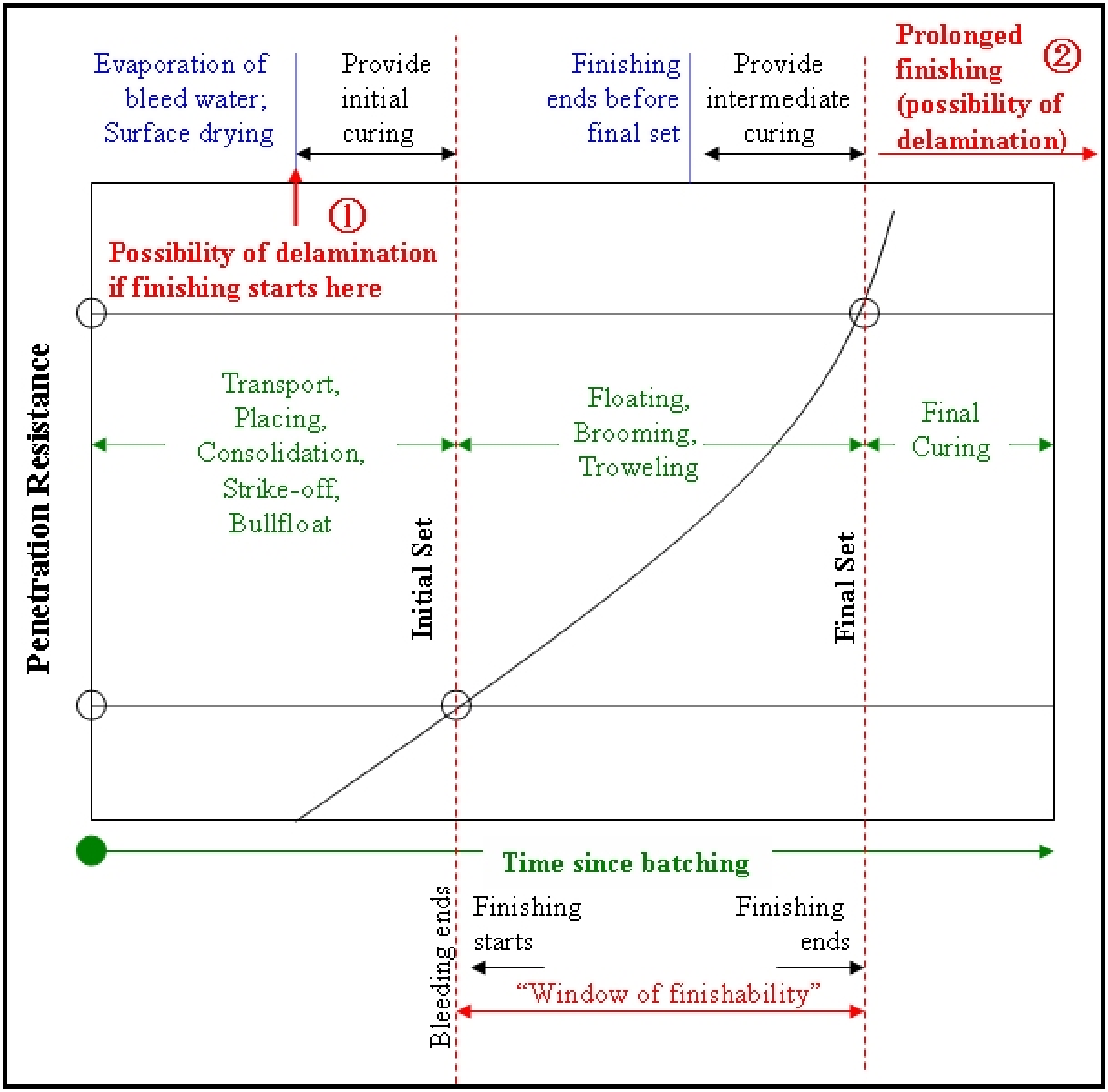
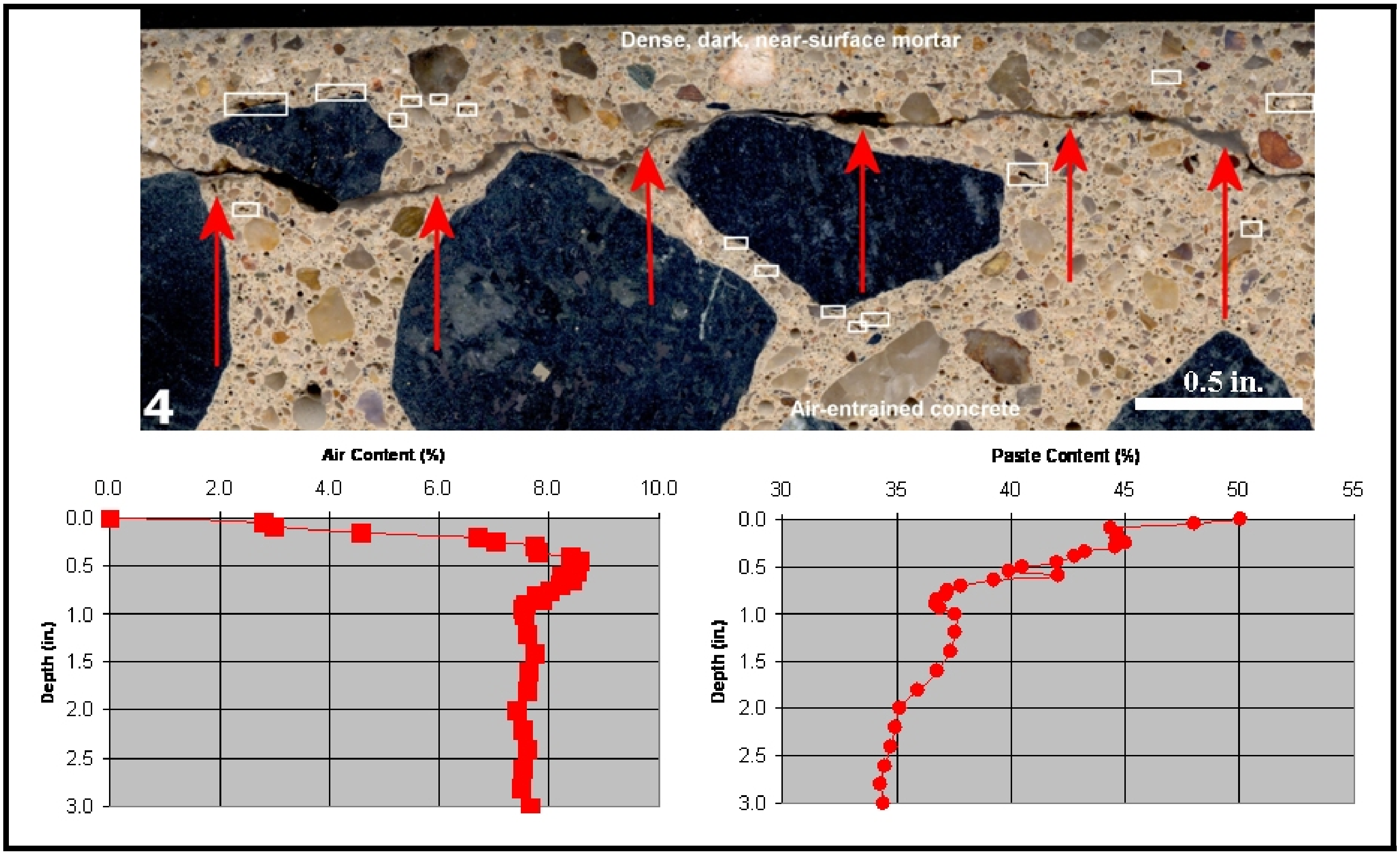


Figure 2: Shown are the importance of: (a) initial curing during the time interval between the evaporation of bleed water and initial setting (prior to finishing) to minimize the moisture loss and surface stiffening before finishing; and (b) intermediate curing during the time interval after the end of finishing but before the final set to keep surface moist and prevent any moisture loss before final curing. The "window of finishability" is the time period between the initial set (and disappearance of bleed water) and the final set. Also shown are successive stages of transport, placement, consolidation, floating, finishing, and curing operations since the time of batching and two situations that can lead to potential delamination. (Adapted from ACI Committee 308R-01 Report on Curing [15])



<u>Figure 3 (Delamination due to use of air entrainment in a concrete slab that has received a machine-trowel finish)</u>: Cross section of a concrete core from a delaminated slab showing the near-surface region down to a depth of 1.5 in. (37.5 mm). Notice: (a) the horizontal plane of delamination oriented parallel to the finished surface (marked by arrows); (b) the dense, dark, low-air, near-surface mortar situated immediately beneath the finished surface and above the plane of delamination; (c) micro-separations ("tears") and elongated distorted voids in the near-surface region associated with the plane of delamination (marked with boxes); and (d) the air-entrained concrete below delamination in the body of the concrete, which was not affected by the trowel finishing. Also shown are profiles of air contents and paste content in the core – notice the significant decrease of air and increase of paste at the top $^{1}/_{2}$ in. (12.5 mm) relative to that in the body. Such variations of air and paste contents are due to finishing manipulations that have embedded the aggregate particles deep inside the concrete (thereby increasing the paste-to-aggregate ratio and paste content), and washed air out of the surface region.

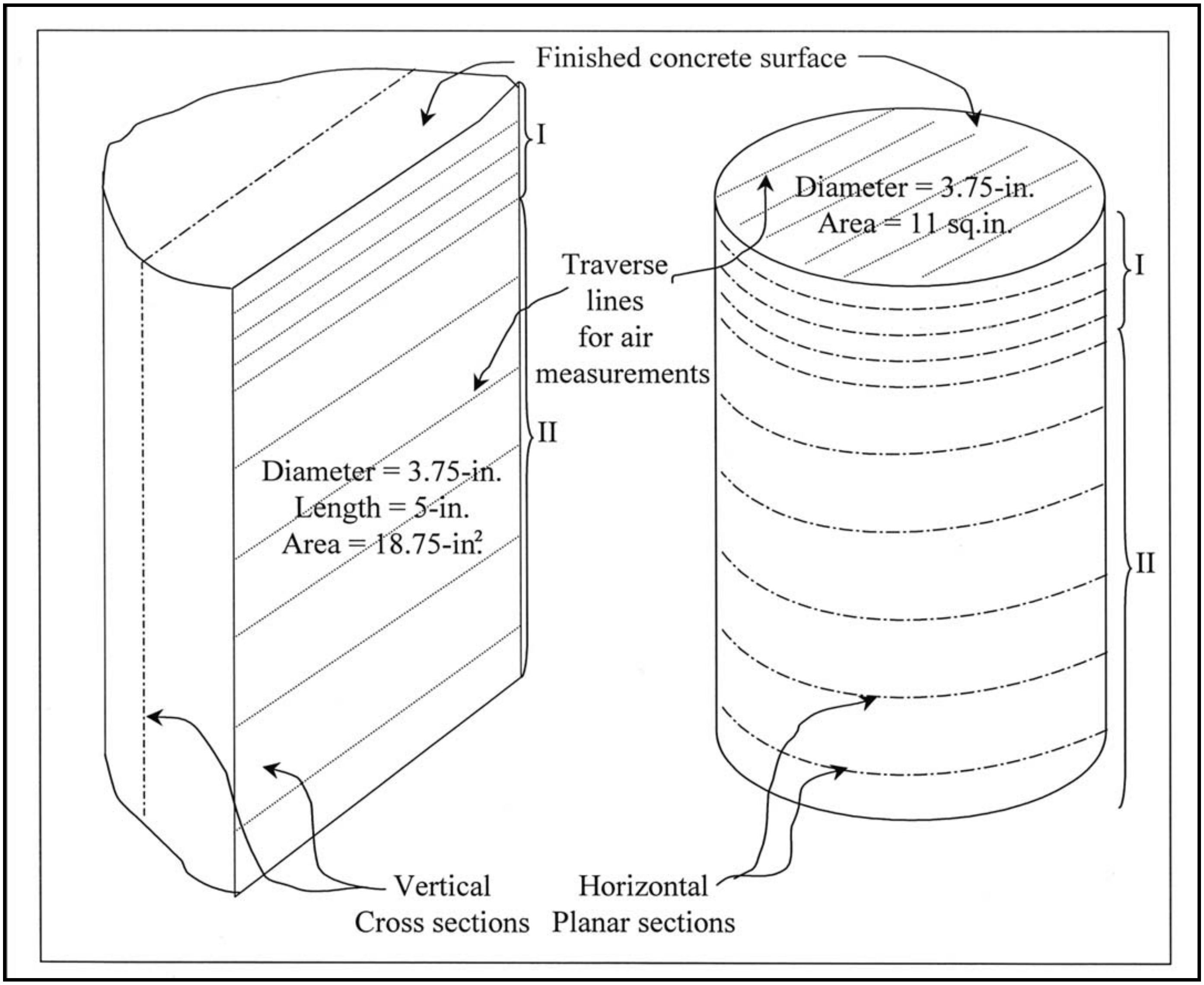


Figure 4: Schematic diagrams showing two different methods of air-void analysis of concrete cores from a delaminated concrete slab. In the left photo, a core is sectioned longitudinally, lapped to smooth fine surface, and air voids are measured on the lapped cross section. Successive vertical cross sections can be prepared for multiple air void analyses on a core to determine the accuracy of measurements on a single cross section. In the right photo, air voids are measured on the top, circular section (representing the finished surface), and in successively deeper circular sections by progressive grinding of the core, or circular sectioning and lapping. In both cases, a large number of closed-spaced traverse lines (left photo) or circular sections (right photo) are utilized in air-void measurements of near-surface concrete (marked by "I"), where air voids show a rapid decrease towards the surface due to trowel-finishing operations. Beneath this near-surface region, in the body (marked as "II") air-void measurements can be done in relatively wide-spaced traverse lines (left photo) or circular sections (right). Results obtained from both methods are usually similar and show a more or less consistent air contents in the body, which are followed by a rapidly decreasing air content in the near-surface trowel-affected zone (in area marked by "I"), where air contents show a sharp reduction down to almost no air at the finished surface. The plane of delamination usually occurs either within zone "I" or at the interface between zones 'I' and 'II'.

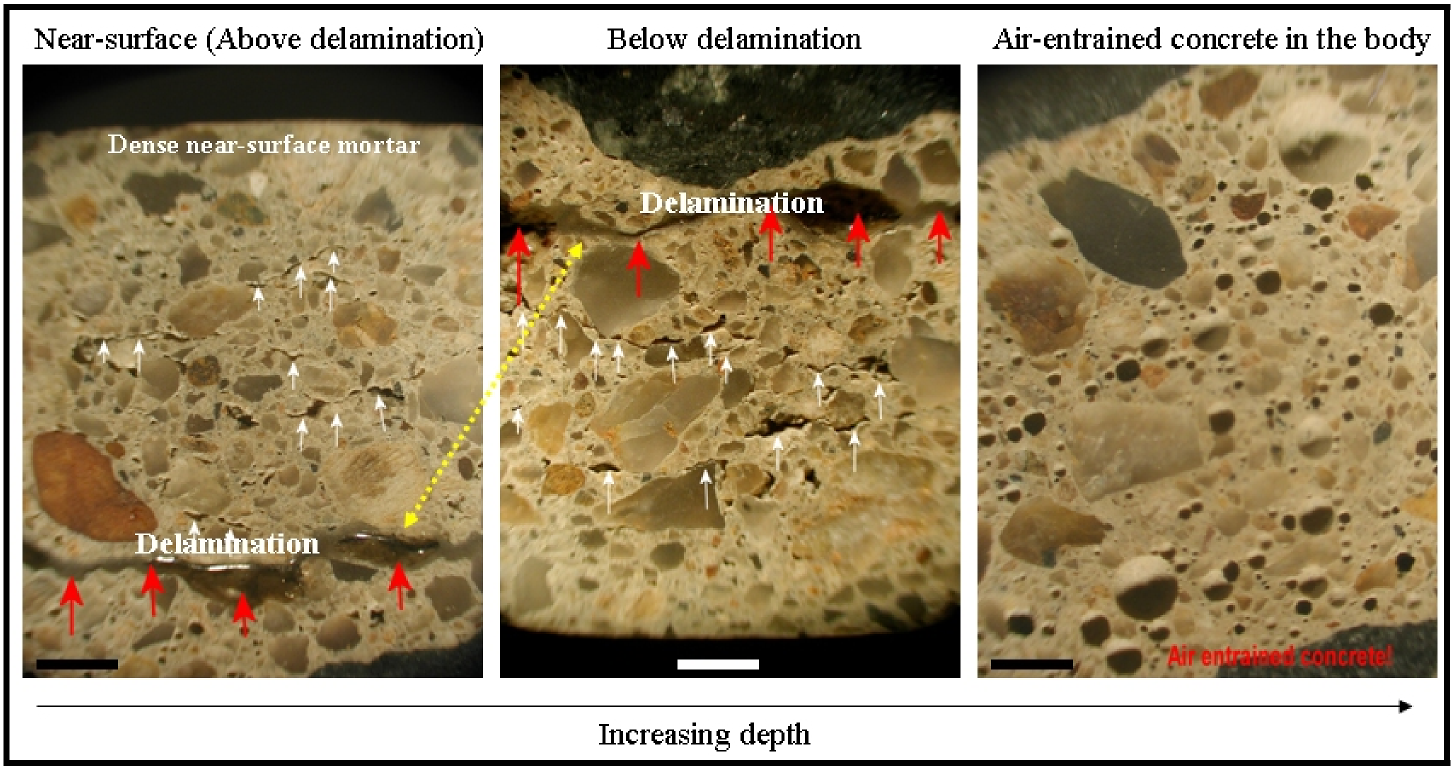
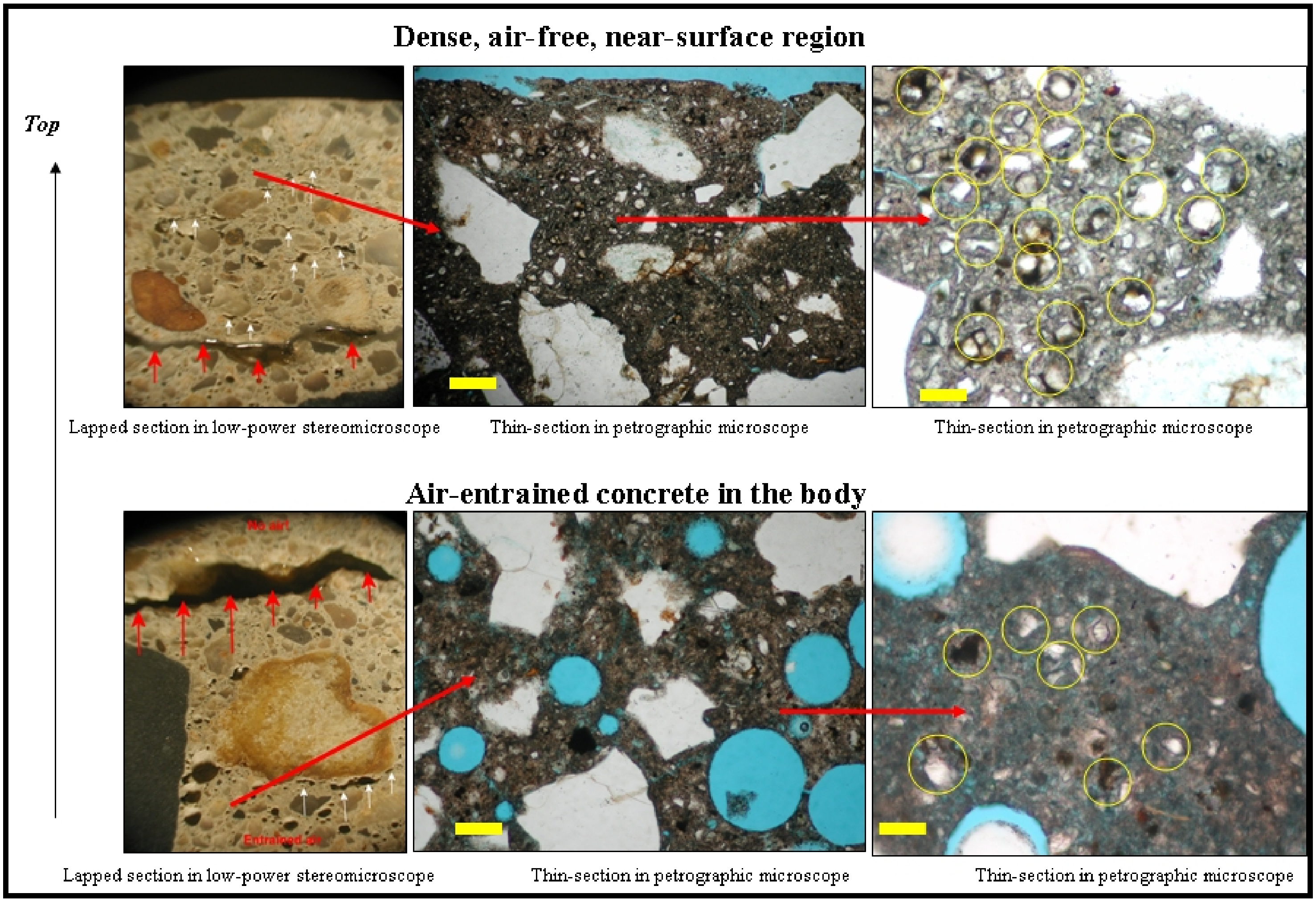


Figure 5 (Delamination due to use of air entrainment in a concrete slab that has received a hard trowel finish): A close view of the cross-section of the core shown in Figure 2: (a) Left Photo - 'micro-separations' as small, elongated or distorted voids (white arrows) below the finished surface, in the dense, near-surface mortar above the delamination (red arrows); (b) Middle Photo – 'micro-separations' beneath the delamination; and (c) Right Photo – Air-entrained concrete beneath the micro-separations, approximately 2 in (50 mm) below delamination. The bars represent $^{1}/_{8}$-in. (3 mm). The portion above the delamination was secured to the concrete by epoxy impregnation. There are no entrained air voids in concretes near and above the delamination due to compression during finishing operations. The photographs were taken by using a stereo microscope at a magnification of 30X.



<u>Figure 6 (Delamination due to the use of air entrainment in a concrete slab that has received a hard trowel finish)</u>: Lapped and thin-section photomicrographs showing the effect of trowel-finishing. The top three photos are of near-surface region showing the dense, low *w/c* mortar that contains abundant residual cement particles in the paste (circled). The bottom three photos are of the interior concrete situated below delamination, which is air-entrained and contain dense paste but not as dense as that in the near-surface region and residual cement particles (circled) are not as abundant as in the near-surface region. Field widths of thin section photomicrographs are 1.5 mm.

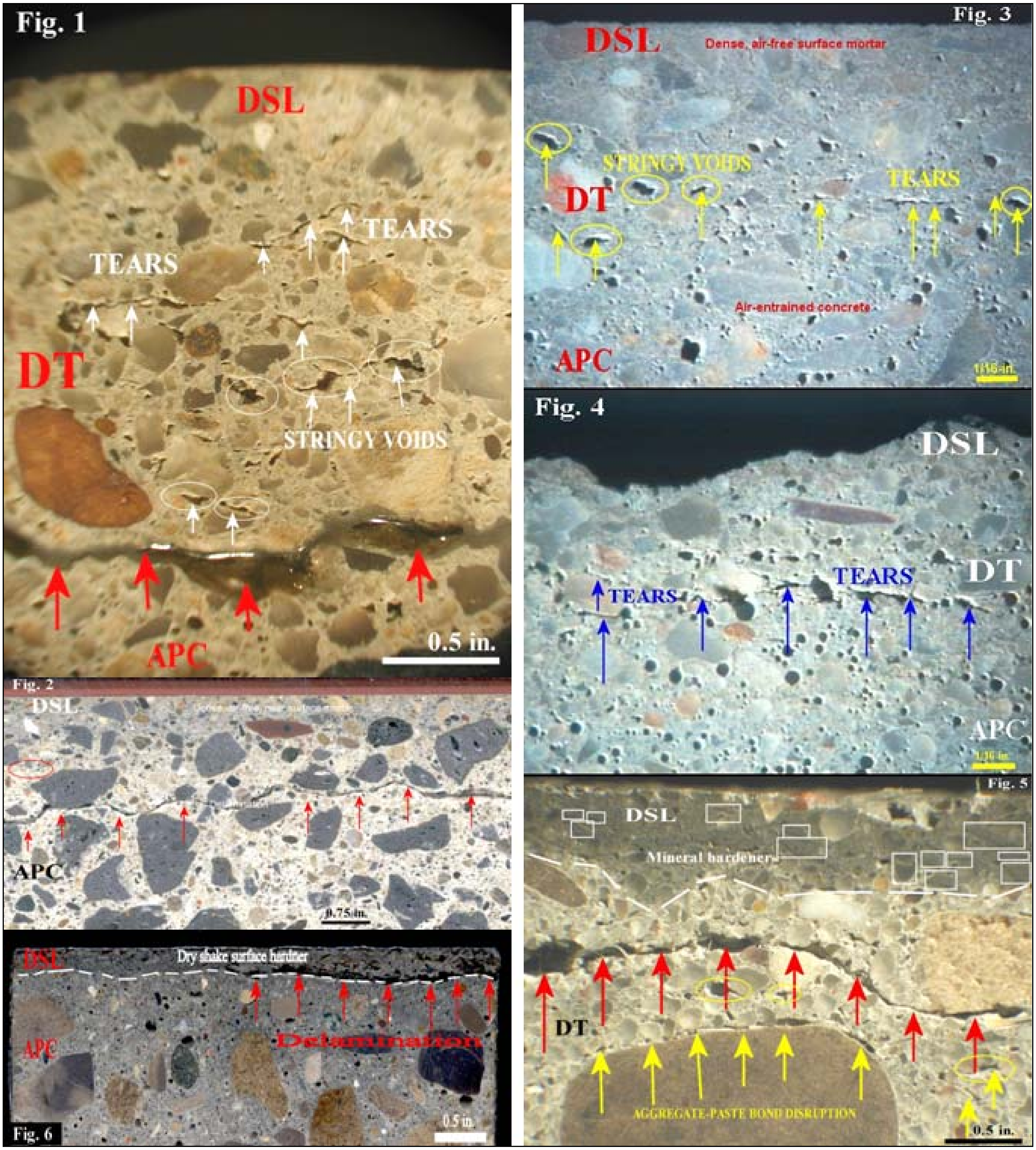


Figure 7: Microstructural characteristics of a delaminated machine-trowel-finished concrete slab, depicting three distinct zones, as described by Lankard [41] – (a) The densified surface layer (DSL), situated above the plane of delamination, and characterized by very high paste content, very low *w/c* and air content compared to that in the body; (b) the distorted layer (DT) associated with irregularly shaped voids, tears, and aggregate-paste bond disruptions (air content is higher than that in DSL but lower than or similar to that in the body, usually have a strong air profile); (c) the trowel-affected zone (TAZ), which is the combined thickness of DSL and DT; and (d) as-placed concrete (APC), which is essentially the interior concrete not affected by finishing, representing the majority of the slab, where the air content and other proportions are similar to the concrete being placed.

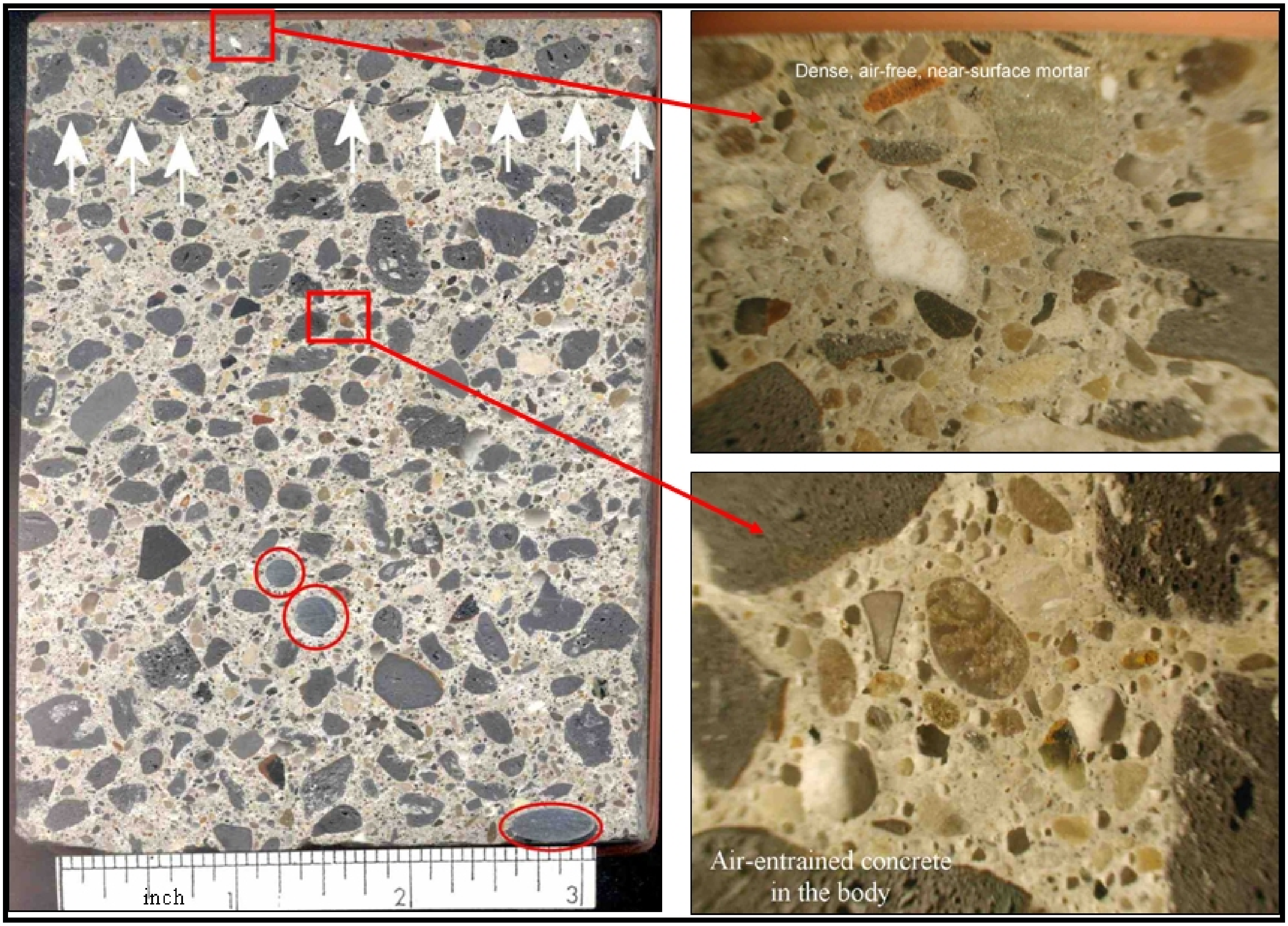
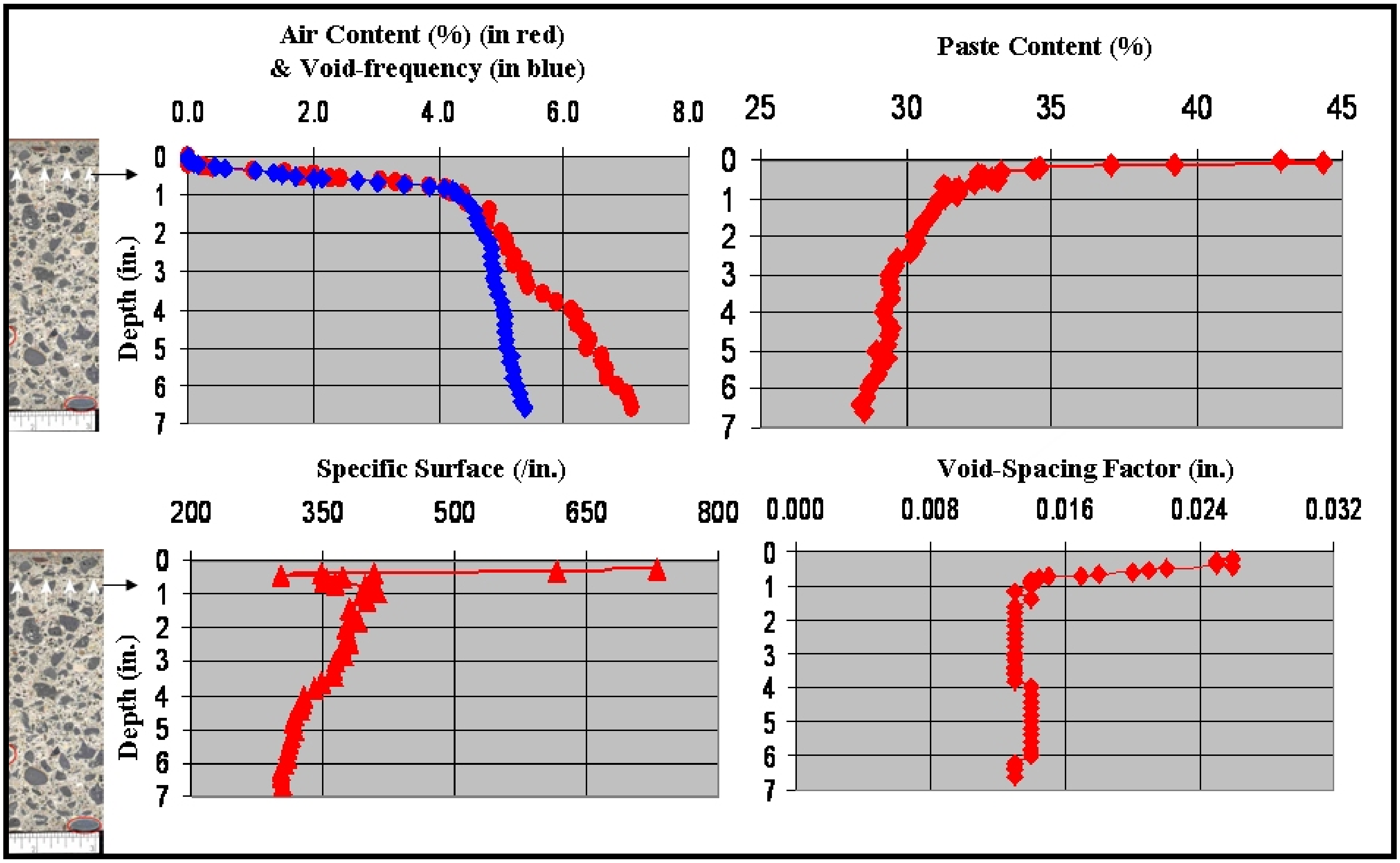


Figure 8 (Delamination in a lightweight aggregate concrete slab that has received a hard trowel finish): Cross-section of a concrete core from a delaminated lightweight aggregate concrete slab showing the delamination (white arrows in the left photo) and contrasting features of the dense, low-air, near-surface region and the less dense, air-entrained interior concrete. The right photos are the enlarged views of the boxed areas in the left photo, taken by using a stereomicroscope (field widths of right photos are 20 mm). Within the circles and ellipse in the left photo are wire meshes in the concrete.



<u>Figure 9 (Delamination in a lightweight aggregate concrete slab that has received a hard trowel finish)</u>: Shown are the profiles of air-void parameters in the core of Figure 8. Notice the significant decrease of air content and void frequency at the top 1/2 in. (12.5 mm) and increase of other parameters. Such variations are due to machine-troweling operations, and are indicative of reduction in size and abundance of coarse air voids by troweling. The left photos are the vertical slices of the cross-sections from Figure 8 showing the depth of delamination (in arrows) relative to the depth where air-void parameters started to change [approximately at a depth of 1 in. (25 mm)].

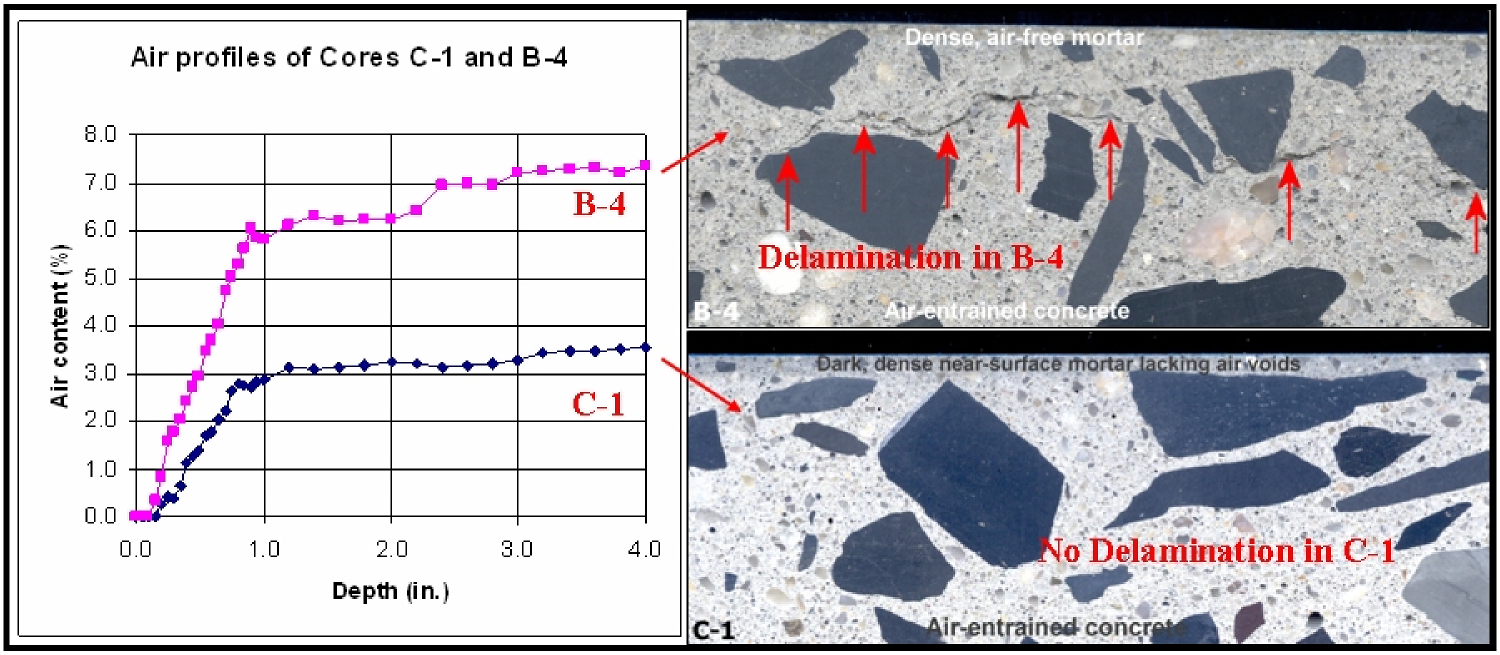


Figure 10: Cross-sections and air profiles of two cores from an indoor delaminated concrete slab showing the importance of keeping the air content low to prevent delamination, when the slab is trowel-finished. Core C-1 is from a good (i.e., ring-sounded) and Core B-4 is from an adjacent bad (i.e., hollow-sounded) area. The hollow sound is due to the presence of a delamination in B-4 at a depth of $^{1}/_{2}$ to $^{3}/_{4}$ in. (12.5 to 19 mm). The air profiles show significant difference in air contents in two cores from the same slab. The high air content in Core B-4 has contributed to the delamination, whereas due to low air content in Core C-1, the slab in this location remained sound. Industry recommends a total air content to be less than or equal to 3 percent, if the slab is anticipated to receive a hard trowel finish.

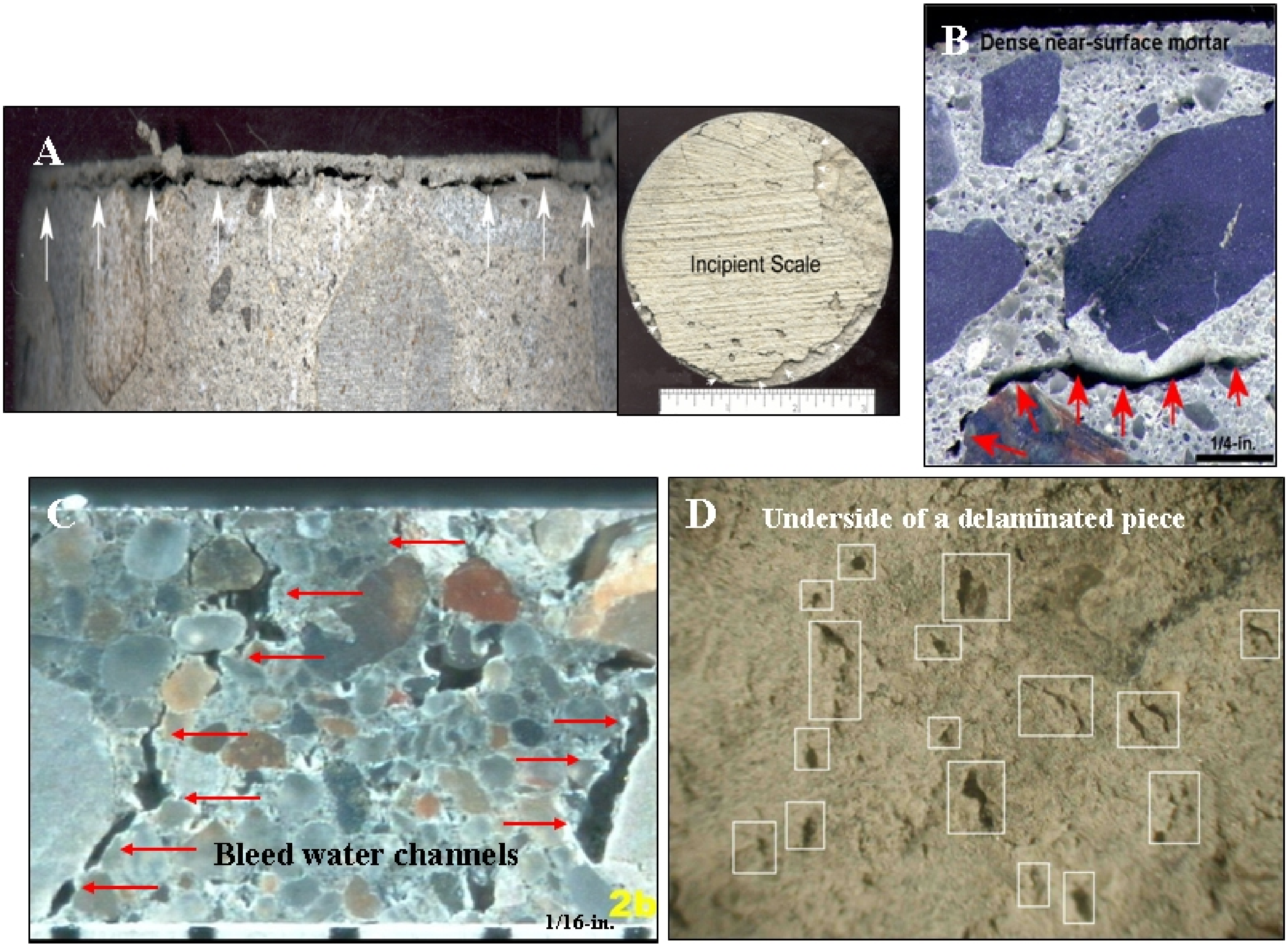


Figure 11 (Delamination due to premature finishing prior to the cessation of bleeding): Shown are evidence of delamination due to premature finishing and entrapment of bleed water beneath the finished surface: (a) a distinct gap between the finished surface and the body of a core, (b) horizontal bleed water voids below a dense surface mortar, (c) vertical bleed water channels in the cross-section of a core, and (d) irregularly shaped voids at the underside of a delaminated piece due to entrapment of bleed water under the delaminated portion.

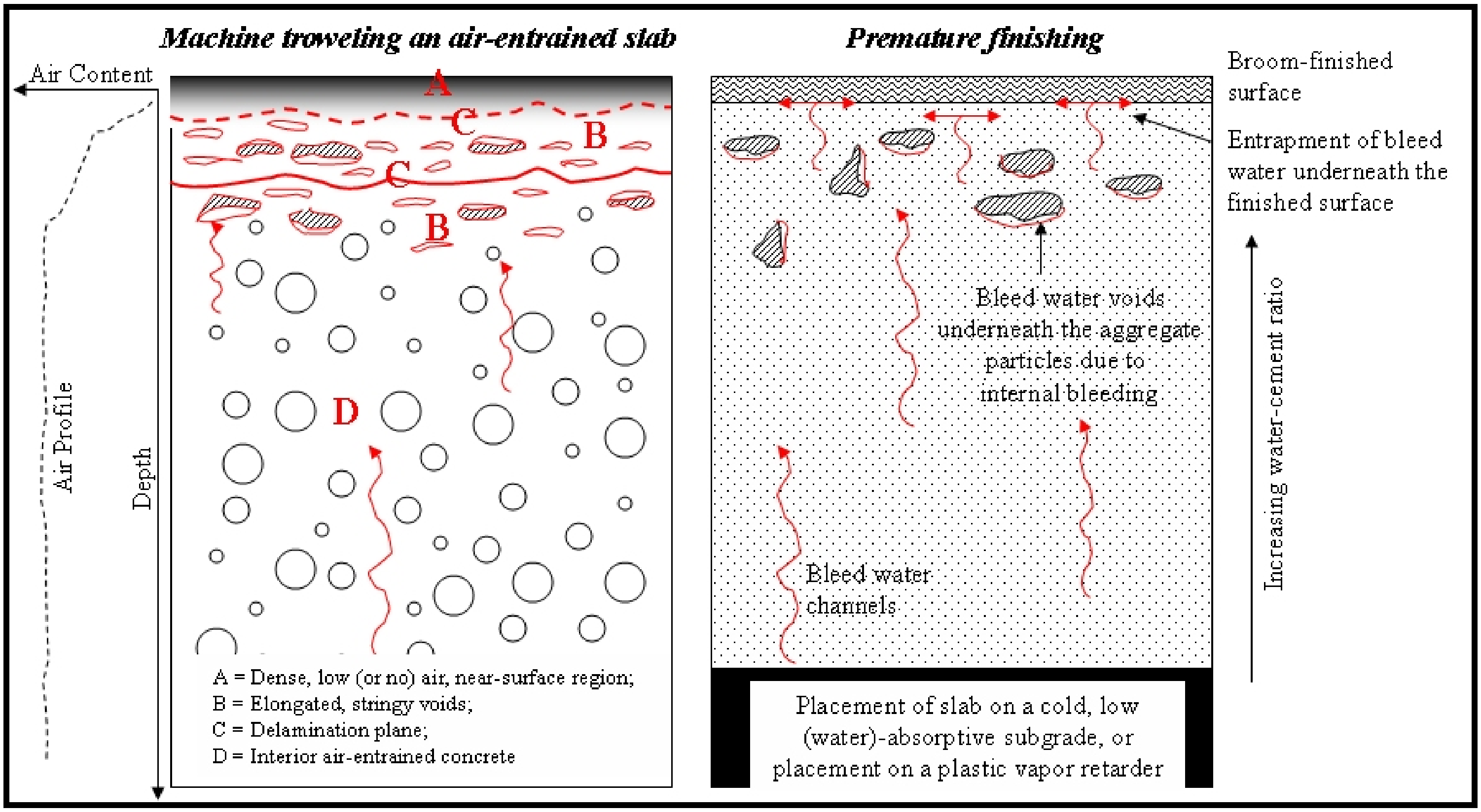


Figure 12: Schematic cross sections of concrete slabs (not drawn to scale) showing two different scenarios of delamination due to machine troweling an air-entrained slab, and premature finishing and entrapment of bleed water beneath the finished surface. The left scenario, depicting the loss of air at the surface region by hard troweling operations, is common in many indoor concrete slabs that have been mistakenly air-entrained (or, air was incorporated to prevent surface distress during an early construction period in an open cold weather condition), and subsequently delaminated. The right scenario is common in many indoor and outdoor slabs, irrespective of air entrainment, where initiation of finishing prior to the cessation of bleeding has caused an entrapment of bleed water beneath the finished surface and, subsequently, delamination of the finished surface from the rest of the body.

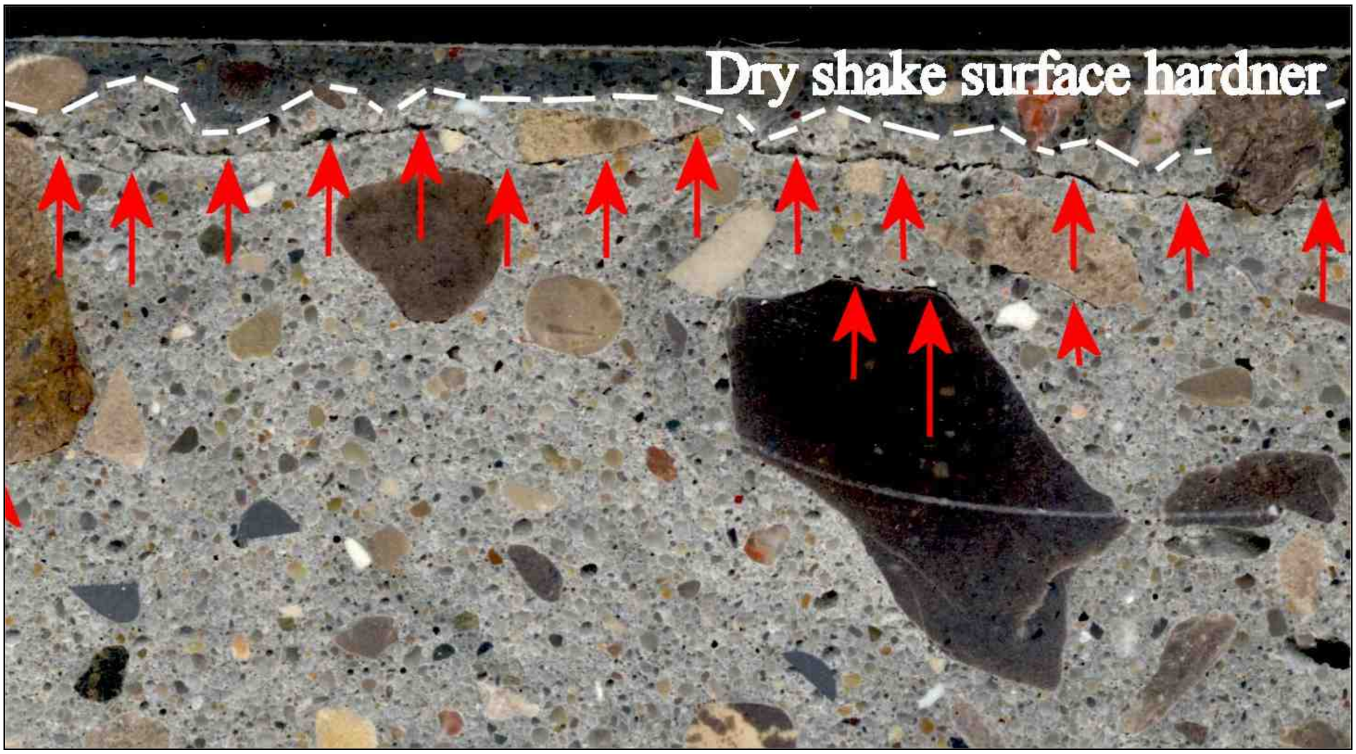


Figure 13: Cross section of a concrete core from a delaminated machine-trowel-finished industrial concrete floor, which has received a "dry shake" mineral surface hardener. The plane of delamination (marked by red arrows) is situated beneath the dense, dark gray surface region [the top $^1/_8$ in. (3 mm)] where the hardeners are present. Prolonged finishing operations (beyond what was needed to incorporate and embed the hardeners into the concrete), probably to achieve the anticipated floor flatness, has caused an eventual development of a plane of separation between the near-surface trowel-affected zone (i.e., the portion above the plane of delamination) and the interior concrete not affected by finishing.

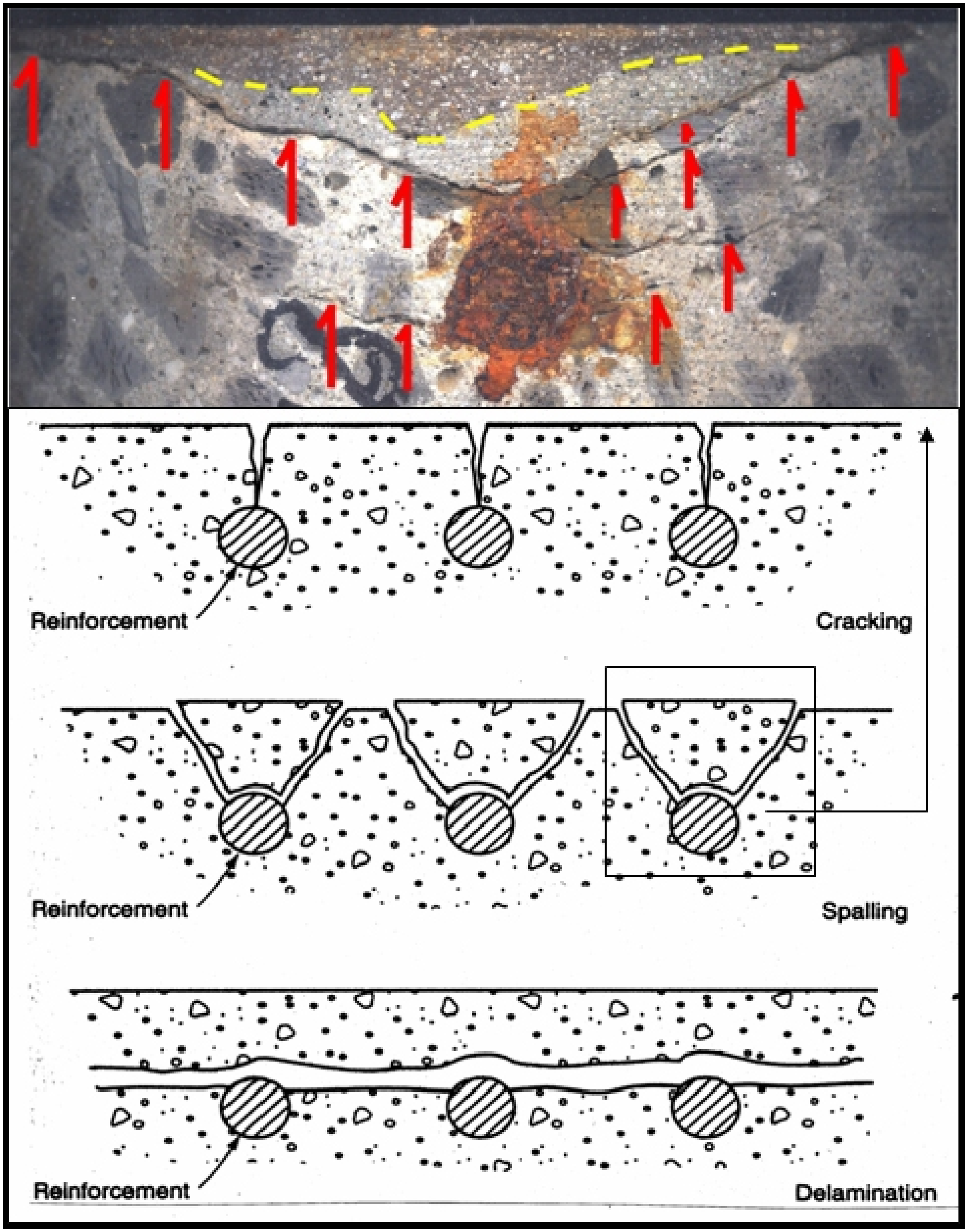


Figure 14: Corrosion of reinforcing steel can cause cracking, spalling, and eventually delamination. The top figure shows spalling of concrete (marked by arrows including the repair patch i.e., the portion above the yellow dashed line) in a core above a corroded rebar, which can eventually lead to delamination, as shown in the bottom diagram (adapted from Neville's *Properties of Concrete* [31])

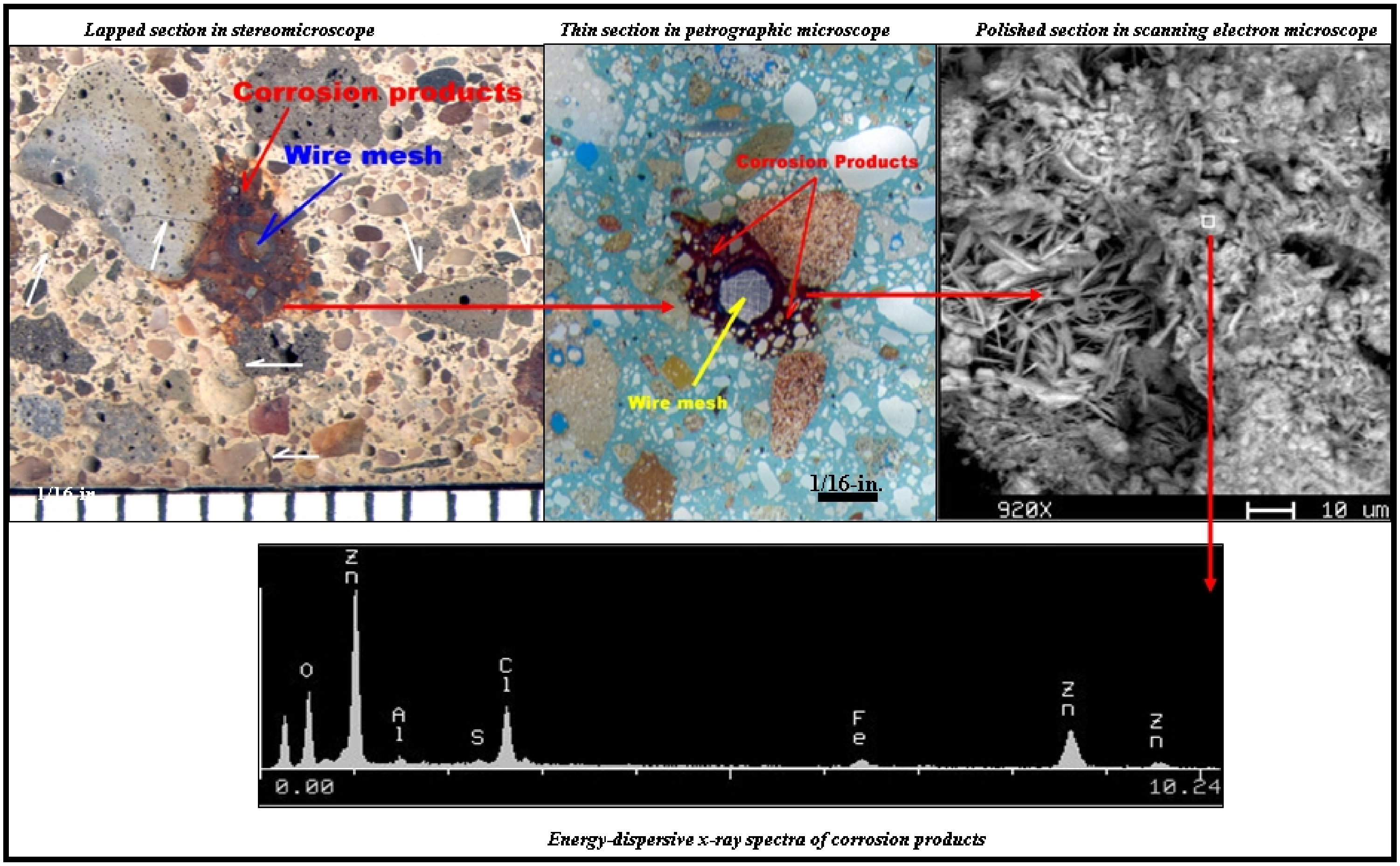


Figure 15: Identification of the extent of corrosion and the composition of corrosion product by petrography. The two top left photos of lapped and thin-sections show the extent of the reddish brown corrosion product from a wire mesh into the paste and cracking associated with corrosion. The rightmost photo shows the plate-like morphology of the corrosion products in backscatter electron image of a scanning electron microscope. The composition of the boxed area in the top right photo is shown in the x-ray energy-dispersive spectrum of SEM (bottom photo). The corrosion product contains zinc chloride from corrosion of the galvanized wire.

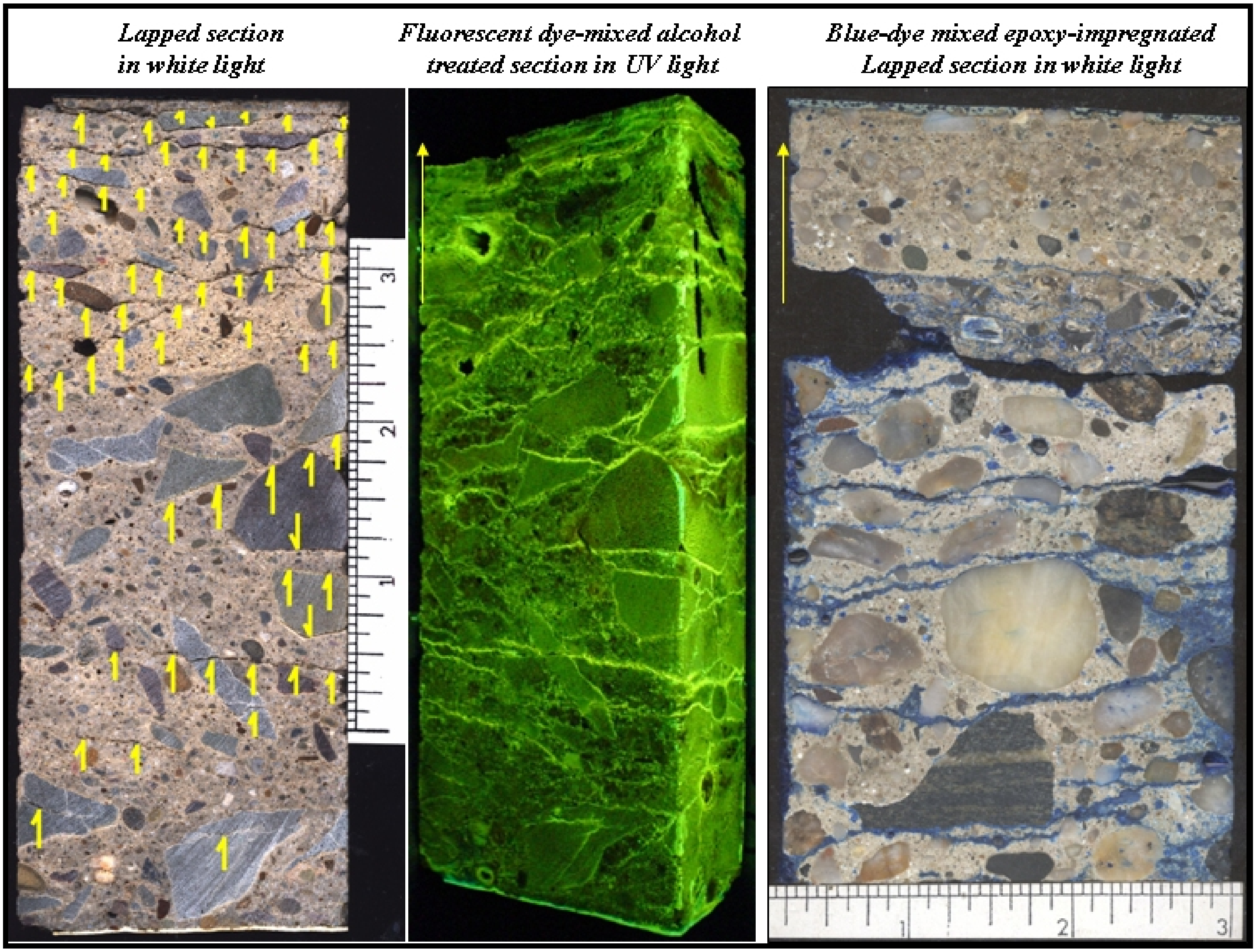


Figure 16: Delamination due to cyclic freezing and thawing of outdoor concrete slabs at critically water-saturated conditions. The left and middle photos are of the same cross-section of a core from a bridge deck shown in different modes of sample preparation. The right photo shows cross-section of a core from a parking garage, where severe cracking throughout the depth of the concrete substrate has apparently failed the repair mortar coat at the top.