

CONCRETE SCALING – A CRITICAL REVIEW

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ABSTRACT

Scaling, i.e., local flaking or peeling away of the near-surface portion of a concrete slab is the most common type of surface distress, especially in areas exposed to cyclic freezing and thawing, and deicing chemicals. A comprehensive evaluation of factors responsible for concrete surface scaling is presented. The article gives a close look to the influences of: (a) concrete materials, proportions, and properties (air content, air void system, aggregate, cement paste, aggregate-paste interface, compressive strength, water-cementitious materials ratio, degree of saturation of concrete, and chemical admixtures); (b) construction practices (consolidation, finishing, curing, hot and cold weather protections, drainage, and surface treatments); (c) concrete maturity; and (d) deicing salts (salt type, concentration, timing of exposure) on scaling. The evaluation is based on numerous case studies on field reconnaissance and laboratory investigation of concrete scaling, where holistic approaches incorporating all possible factors for scaling were considered.

The results show that in a cyclic freezing and thawing environment, the most common causes of scaling are related to one or a combination of the following factors: (a) poor quality of concrete (e.g., having no or low air content, poor air-void system, unsound aggregates, etc.), (b) improper construction practices (e.g., improper finishing, inadequate curing), (c) exposure to corrosive (e.g., magnesium or ammonium-based) salts, (d) exposure to the common sodium or calcium chloride based salts at an early age prior to the attainment of maturity, and (e) exposure of an inherently poor quality and/or poorly constructed concrete to deicing salts.

Surface scaling in an apparently non-freezing environment can occur by improper finishing practices or, by reversible phase transformations of soluble salts (e.g., of sodium sulfate or carbonate) and zeolites (e.g., laumontite) between less-hydrous (or anhydrous) and more hydrous states during cyclic wetting and drying.

Fulfilling the common industry recommendations, e.g., of air content, compressive strength, and water-cementitious materials ratio may not necessarily guarantee the necessary scaling resistance unless a comprehensive evaluation of the influences of all possible factors related to concrete mixture, construction practices, and the environment on scaling are exercised, and, the concrete is accordingly designed, placed, finished, cured, and matured for the maximum durability.

INTRODUCTION

The ACI Committee 116R report [1] on 'Cement and Concrete Terminology' describes concrete scaling as 'local flaking or peeling away of the near-surface portion of hardened concrete or mortar' and rate it as 'light', 'medium', 'severe', and 'very severe' depending on the loss of surface mortar down to depths of less than 5 mm, 5-10 mm, 5-10 mm to 10-20 mm around aggregates, and greater than 20 mm, respectively. The loss of surface mortar usually exposes the near-surface coarse aggregate particles, except when the scaling is rated as 'light'.

Scaling of concrete roadways, pavements, sidewalks, driveways, decks, and other slabs is a common problem in outdoor construction exposed to cyclic freezing and thawing and deicing salts. The blame, usually, circulates around the quality of the concrete supplied (i.e., to the ready-mixed supplier), the methods of construction followed (i.e., to the contractor), or salts applied for snow removal (i.e., to the owner). Among these three, the most common culprit is generally *assumed* to be the deicing salts. The dispute is usually settled by field investigation, detailed petrographic examinations, air-void analysis, and chloride analysis of concrete cores, chunks, or saw-cut sections from the scaled and sound areas of slab, and investigating various factors related to materials, workmanship, salts, and environment responsible for scaling.

For resistance to scaling in a severe weather environment of cyclic freezing and thawing, concrete should have the following *essential* characteristics (see Table 1 and Figure 1 for a holistic approach to scaling with a complete list of all possible factors to be considered for a scale-resistant concrete):

- (a) Concrete should be air-entrained for the protection of the paste during freezing. Concrete should have a good air-void system consisting of numerous fine, discrete spherical and near-spherical air voids of sizes up to 1 mm, the majority of which should be very fine, closed-spaced, and uniformly distributed to have a specific surface of at least $600 \text{ in}^2/\text{in}^3$ ($23.6 \text{ mm}^2/\text{mm}^3$), and a maximum void-spacing factor of 0.008 in. (0.2 mm). The total air content should be kept at a minimum optimum level as long as the air void spacing factor requirement is fulfilled. For a high strength concrete having a water-cementitious materials ratio of 0.30 or less, however, frost resistance can be achieved even at a low air content and a higher than recommended 0.008 in. (0.2 mm) void spacing factor, because the paste has a very low permeability to moisture and a low amount of freezable water.
- (b) Concrete should be made using well-graded, well distributed, and frost-resistant aggregates. Well-graded aggregates optimize the paste content and reduce the amount of air needed for the protection of the paste. Aggregates should be frost resistant to prevent popout and other unsoundness during freezing at critically water-saturated conditions.
- (c) Concrete should be properly placed, finished, and cured. Concrete should be well consolidated and 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. The finished surface should be well-cured to provide adequate cement hydration and necessary development of strength and other desirable properties at the surface to create a dense, near-impermeable, and moisture-tight concrete, which is resistant to distress during freezing.
- (d) Concrete should be matured, i.e., it 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

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

Concrete that fulfills *all these conditions* should be durable in a cyclic freezing and thawing environment, even in the presence of common sodium or calcium chloride-based deicing salts that do not usually cause any chemical corrosion of paste. Concrete that lacks even one of these conditions is susceptible to scaling, and more so in the presence of salts.

FIELD AND LABORATORY STUDIES FOR INVESTIGATION OF CONCRETE SCALING

Field Reconnaissance

A detailed field reconnaissance is helpful and sometimes essential in an investigation of scaling. A field survey:

- (a) Documents existing surface conditions;
- (b) Determines the depth, severity, extent, and locations of scaling;
- (c) Collects photographs of surface conditions;
- (d) Collects all necessary background information about the project including information about concrete mixture, time of placement, maintenance and performance history; and
- (e) Selects appropriate locations for samples for detailed laboratory investigations.

Saw-cut sections, broken pieces, or, more commonly 3 to 4 in. (75 to 100 mm) diameter concrete cores drilled through partial or entire depth of the slab are taken from both scaled and relatively sound or less distressed areas for laboratory examinations. Thin, sheet-like masses of loose scales of finished surfaces, either completely de-bonded or loosely adhered to the main body of concrete, if present, are also helpful in providing information about the conditions of concrete at the surface.

Laboratory Studies

Petrographic examinations (*a la* ASTM C 856) and air-void analyses of hardened concrete (*a la* ASTM C 457) are the two most common laboratory procedures practiced during an investigation of scaling. These two methods, related to visual and detailed microscopical examinations of concrete are often adequate to diagnose many factors responsible for scaling. The concern of involvements of chloride-containing deicing salts in scaling is often verified by acid or water soluble chloride analysis of concrete from the surface region and from interior at regular depth intervals. Compressive strength, deicing salt scaling resistance, and freeze-thaw durability of concrete are sometimes verified by ASTM C 42, C 672, and C 666 tests, respectively. Following are brief descriptions of some of these methods:

Petrographic Examinations

Petrographic examinations involve detailed examinations of:

- (a) Field conditions and photographs of concrete surface distress to evaluate the extent and severity of scaling;
- (b) Concrete samples (core, saw-cut section, scales, etc.) with a hand lens and a low power stereomicroscope;

- (c) Fresh fractured sections, saw-cut surfaces, and lapped sections of concrete in a low power stereo microscope;
- (d) Oil immersion mounts and large-area (usually 50 × 75 mm size) thin sections (often impregnated with a blue or fluorescence dye to highlight porous areas in concrete) in a petrographic microscope;
- (e) Polished thin sections, solid samples, or fresh fractured surfaces in a scanning electron microscope equipped with elemental analysis facilities; and, sometimes,
- (f) X-ray diffraction analysis of scales or pulverized concrete samples for the detection of any specific material of interest.

Petrographic examinations evaluate:

- (a) The overall quality and condition of concrete at the surface region and in the interior;
- (b) The depth and severity of scaling;
- (c) The air void system of concrete and its role in scaling resistance;
- (d) Evidence of finishing and curing improprieties at the surface region, which can contribute to the scaling;
- (e) Influences of various concrete constituents and proportions in scaling (e.g., aggregate type, soundness, reactivity, gradation and distribution, cementitious materials content, water-cementitious materials ratio); and
- (f) Possible involvements of deicing salts in scaling.

Air-Void Analysis

Air void analysis involves:

- (a) Preparation of lapped cross section of a concrete slab or core (sectioned perpendicular to the finished or exposed surface) by grinding a saw-cut section with successively finer size grinding abrasives (SiC, Al₂O₃, or diamond) on a lapping plate;
- (b) Examinations of smooth, flat, cleaned, and dry lapped section in a stereomicroscope equipped with facilities for reflected-light illumination; and
- (c) Measurements of air-void parameters (air content, void frequency, paste-air ratio, specific surface, and air void spacing factor) by linear-traverse and/or modified point count method as described in ASTM C 457.

In linear traverse or modified point count method of ASTM C 457, a properly prepared lapped section of concrete is placed on an X-Y stage (which moves in E-W and N-S directions, either manually or with stepper motor controllers), and the section is examined with a high-power stereo microscope at a magnification of 70 to 100X. The linear traverse method involves measurements of chord intercepts of air voids, paste, and aggregates during a series of parallel linear traverses on a lapped section, calculations of volume proportions of each constituents from the cumulative chord intercept on each constituent to the total traverse length at the end of the test, and calculations of air void parameters from the collected data. The modified point count method involves measurements of total number of air voids, aggregates, and paste encountered at stops at regular intervals during a series of parallel traverses across the lapped section, measurements of total number of air voids encountered (including voids encountered at regular stops) during traverses, calculation of volumetric proportion of constituent from the total number of stops at each constituent to the total points counted over the entire test, and calculations of other air void parameters from these measured and calculated data.

In addition to these “manual” methods of ASTM C 457, a number of automated image analyses methods have been proposed [2], which involve examinations of air voids on a lapped surface by an image capture device (a camera attached to a stereo microscope or a flat bed scanner) and calculations of air void parameters by an appropriate, user-defined software. In some of these methods, the lapped surface is treated with a black ink and a white paste or powder to highlight the air voids as white areas against the dark background of paste, aggregates and other constituents in concrete.

Chloride Content Analysis

Chloride contents (acid-soluble chloride content by ASTM C 1152 or water-soluble chloride content by ASTM C 1218) of the surface (usually the top $\frac{1}{2}$ in.) and interior concrete at regular intervals are sometimes determined for an assessment of whether or not scaling is a consequence of high chloride contents at the surface region compared to that in the body, such as from the applications of chloride-containing deicing salts.

Compressive Strength Testing

Compressive strength tests of concrete cores or saw-cut sections (*a la* ASTM C 42) collected from the field, or, strength test of concrete cylinders cured in the laboratory (*a la* ASTM C 39) is sometimes necessary to verify whether the concrete has the necessary and adequate strength for scaling resistance, or has attained the design strength prior to the exposure to salts and snow.

Deicing Salt Scaling Resistance Tests

The deicing salt scaling resistance test of a concrete surface *a la* ASTM C 672 (the ponding method) attempts to experimentally duplicate the natural environment of cyclic freezing and thawing of concrete in the presence of salts by placing a $\frac{1}{4}$ in. (6 mm) deep pond of 4 percent calcium chloride solution on the flat, top finished surface of a core or a saw-cut section having a surface area of at least 72 sq. in. and a depth of at least 3 in. After a drying period of 14 days at ambient laboratory air at 21 to 25°C and 45 to 55 percent relative humidity, the surface to be tested is covered with salt solution and the sample is exposed to a series of 50 daily freezing and thawing cycles, each constituting a 16 to 18 hours of freezing period followed by 6 to 8 hours of thawing period at $23 \pm 2^\circ\text{C}$ ($73.5 \pm 3.5^\circ\text{C}$) at a relative humidity of 45 to 55 percent. The scaling-resistance is qualitatively determined by a visual arbitrary rating of 0 to 5 where “0” indicates no scaling and “5” indicates severe scaling. At the end of each series of 5 cycles, the surface is flushed, the solution on top is replaced, sample is then weighed, and visually rated. Loose scaled off pieces at the surface, if any, are sometimes collected, dried, and weighed at regular intervals during the test by many laboratories to increase the reliability of this test and a quantitative assessment of scaling beyond the subjective judgment of visual rating.

Freeze-Thaw Durability Tests

The overall resistance of concrete to cyclic freezing and thawing is evaluated by ASTM C 666 or various state-specific tests (e.g., New York State DOT Test 502-3P) where core or saw-cut prisms of hardened concrete are either completely immersed in water (in ASTM C 666) or in a brine solution (in ASTM C 666 or NYS-DOT test) and exposed to cyclic freezing and thawing, or frozen in air and thawed in water (C 666) – the temperature extremes are 0 to 40°F (4.4 to –17.8°C) for C 666 and –10°F to 70°F for NYS-DOT test. Durability is measured by the loss of mass (in both tests), length change (in C 666), or loss of dynamic modulus of elasticity of concrete (in C 666).

Background Information

In addition to the above-mentioned laboratory tests and field survey, collection of relevant background information about the project is very important for investigating the roles of various factors in scaling such as:

- (a) Concrete mix design including all solid and liquid components, mineral and chemical admixtures, proportions, manufacturers' datasheet for any specialty admixtures used;
- (b) Concrete placement temperature, weather condition, slump, air content, and other fresh concrete properties measured in the field during placement;
- (c) Reports of tests performed in the laboratory prior to the investigation, such as compressive strength of concrete cylinders prepared in the field during placement, or of concrete cores taken from the structure, any test results available for the concrete ingredients (e.g., cement mill report, aggregate test report);
- (d) Time of placement in the year, age;
- (e) Drainage condition, location of scaling in the field;
- (f) Locations of sound and scaled areas;
- (g) Permanence and maintenance history of the structure; and
- (h) History of usage of deicing chemicals, type of chemicals used.

Not all these above-mentioned information are essential for scaling investigation but many of these information are sometimes very relevant to a specific investigation, which play a crucial role and cannot otherwise be obtained by laboratory testing.

A holistic approach involving background information, field survey, and detailed laboratory examinations is, therefore, needed for a successful investigation.

Figure 2 provides relative numbers of various case studies on concrete deterioration by the author during a three-year period, where a significant proportion of study involved investigation of concrete surface distress, particularly scaling, mortar flaking, and aggregate popout. Among the investigations on scaling, the most common causes are determined to be due to improper concrete materials (improper air void system, unsound aggregate, etc.), improper construction practices (improper finishing operations or inadequate curing), or exposure to deicing salts at an early age, or to corrosive salts [3, 4].

FACTORS IMPORTANT TO THE SCALING RESISTANCE OF CONCRETE

[A] FACTORS RELATED TO CONCRETE MATERIALS AND PROPORTIONING

Air Entrainment

Air entrainment is necessary for resistance of concrete to scaling in a cyclic freezing and thawing environment. The microscopical entrained air void system in concrete, consisting of numerous, fine, discrete spherical and near-spherical voids of sizes up to 1 mm (usually in the range of 50 to 500µm) provides the necessary protection of paste against distress due to cyclic freezing and thawing. For adequate protection, concrete should have a system of numerous, fine-sized, and close spaced air voids uniformly distributed throughout the paste so that water in the paste can find an air void in a close proximity to escape during freezing or have room to accommodate expansion associated with volume change of water into ice. Several case studies have shown that the absence of entrained air, inadequate amounts of entrained air, or a 'coarse' air void system

(where the voids are wide-spaced) decreases the scaling resistance of concrete, particularly at the surface that tends to become saturated by standing water, poor drainage, or by exposures to deicing salts [3,4]. A properly air-entrained concrete provides a much better resistance to scaling, especially in the presence of deicing salts than a concrete without proper air entrainment. Adequate air entrainment and a good air void system alone, however, cannot guarantee adequate scaling resistance unless the concrete materials, proportioning, construction practices, and concrete maturity are also satisfactory.

Several industry documents (e.g., ACI Committee reports 201 on durability and Committee 318 report on building code requirements of structural concrete) have provided tables of the necessary “total” air contents for freeze-thaw durability of concretes containing different nominal maximum size aggregates and exposed to various environments (Table 2).

It is, however, now a well-recognized fact that a mere conformance to the industry-recommended “total air content” does not necessarily guarantee scaling resistance unless the concrete has a good air-void system, i.e., it is made using a system of uniformly distributed, numerous, very fine, spherical and near spherical entrained voids that are situated close to each other so that the specific surface and the void spacing factor of air voids fulfill the respective industry requirements of at least $600 \text{ in}^2/\text{in}^3$ ($23.4 \text{ mm}^2/\text{mm}^3$) and at most 0.008 in. (0.2 mm).

Figure 3 shows schematic diagrams of air void systems in concrete slabs, where, despite having an adequate amount of total air, only the slab having a good air void system with enough *number* of air bubbles at the surface will be scale resistant. The air void spacing factor (which is half of the average distance that water in the paste has to travel to find a nearest air void) is a far more important parameter for the ultimate freeze-thaw durability of concrete than the mere air content. At fixed air contents, the finer the bubbles (i.e., the higher the number of air voids per unit length) and the closer the voids, the better the air void system is for freeze-thaw durability (Figure 4). The goal is, therefore, to achieve a fine air void system at the lowest possible air content (i.e., at the lowest total air volume when air voids are fine and close enough to satisfy the industry recommendation for air void specific surface and void spacing factor), which will not only provide the freeze-thaw durability but can also provide a strength benefit by reducing the total air content to an optimum amount. Therefore, air content alone does not assure freeze-thaw resistance – a far better measure is the *total air-void system*, which encompasses not only the air content (volume) but also the *number of air voids per unit volume*, which relate to specific surface and the distance between voids (the void-spacing factor). The uniformity of air void distribution throughout the concrete and the overall air void system can be determined by petrographic examinations and air void analysis of the suspected concrete.

Common air-entraining chemicals are: (a) wood derived acid salts such as vinsol resin, wood rosin and resin, and gum rosin; (b) tall oil (mixtures of fatty acids and rosin acids); (c) petroleum distillates (sulfonated hydrocarbons); and (d) fatty acids (vegetable oil acids, animal tallows). Of these, vinsol resin is the most common and the oldest one. New chemicals such as tall oils, fatty acids, gum rosins, and petroleum distillates, however, do not require as much dosage as vinsol resin to stabilize sufficient, very-fine, close-spaced bubbles and a good air-void system – due to increased fineness and decreased closeness of bubbles stabilized by these chemicals, freeze-thaw durability of concrete can be increased significantly at a lower air content than that achieved by a vinsol resin based agent (Figure 6, [5]). These new chemicals can stabilize many very fine bubbles, almost twice the amount than that generated from the older vinsol resin based formulations at the same dosage rate. Therefore, controlled addition of these chemicals can stabilize a very fine air void system, which is essential for freeze-thaw durability. An added benefit of air reduction without affecting the air void system is improvement in compressive

strength, which can be achieved by a modest reduction of total air by 1 to 3 percent. A possible negative-effect of some of these chemicals, however, is excessive air entrainment if the dosage is not controlled, which can reduce the strength of concrete by high air content (Figure 6) and air void clustering at the aggregate-paste interfaces [5]. For such chemicals (specially tall oil or fatty acid-based), the industry specification of air content can be reduced to a conservative 1 percent point from the present industry-recommended minimum air limits of 4¹/₂ percent for a concrete exposed to a severe weather and containing ³/₄ to 1 in. (19 to 25 mm) size aggregates. New chemicals can stabilize a good air void system at an air content as low as 3 percent.

Several case studies by the author have shown that adjacent panels of sidewalks, driveways or other outdoor concrete slabs exposed to similar cyclic freezing and deicing salt environments do not necessarily show consistent scaling behavior (Figure 5, [3]). The panels with good air entrainment and air void systems selectively survive scaling, whereas the ones having a poor air void system fail. Severe scaling in one panel whereas no or minimal scaling in the adjacent panel is explained by the absence of air entrainment, or “poor” air-void system in the scaled panel (due to the placement of a panel having no or low air entrainment adjacent to an air-entrained panel). Figure 5 shows typical case studies of scaling due to: (a) lack of adequate number of entrained air bubbles in an air-entrained concrete (having a coarse air void system); and (b) the presence of low amount of “entrained” air in a concrete. In all these and many other cases, the concrete did satisfy the industry requirement or project specification of “total air content” but still scaled due to improper air entrainment. Certainly, fulfilling the industry requirements of total air content does not guarantee scaling resistance unless the concrete has a good air-void system (particularly an air void spacing factor of less than 0.008 in. or 0.2 mm). This is especially true, when deicing chemicals are present.

Unless the air void system of the surface region is affected by the finishing practices, a clear relationship exists between the air void system in the bulk concrete and its scaling resistance. Finishing practices, however, sometimes reduce the air content at the surface, which may not necessarily affect the air-void system and its role in freeze-thaw durability as long as the finishing-induced air loss is restricted to the removal of coarse air voids without affecting the specific surface and void spacing factors of the air void system.

Aggregates

The resistance of concrete to distress due to cyclic freezing and thawing depends not only on the resistance of paste but also of aggregates to distress, which constitute more than 65 percent by volume of concrete. Durability of concrete aggregates during freezing depends on properties such as porosity, water absorption, permeability, pore structure, and modulus of elasticity. A highly absorptive aggregate may absorb enough water to fill all pore spaces (i.e., becomes critically saturated) and cannot accommodate the expansion and hydraulic stresses that occur during freezing of water, resulting in fracturing of the particle and possible disintegration of concrete if enough of such unsound particles are present.

The size, shape, surface texture, and grading of the aggregates are also important for scaling resistance. Concrete containing well-graded aggregates requires less paste for filling the interstices between the particles, and hence, less air for freeze-thaw resistance than the concrete having poorly graded aggregates. All fine and coarse aggregates should meet the requirements of ASTM C 33, “Standard Specification for Concrete Aggregates”. Rough-textured and angular aggregates require more paste than the smoother and rounded ones at the same water-cement ratio (due to the increased void content of compacted angular aggregates). Finer aggregates require

more paste than the coarser ones (due to increased specific surface of aggregates to be coated with paste).

Aggregates that are frost resistant, have high modulus of elasticity, and do not show significant volume changes relative to the volume changes of paste during cyclic freezing and wetting are more appropriate to use in concrete for scaling resistance than the unsound aggregates having poor quality, soft, porous, frost-prone particles, and low modulus of elasticity. Usually, sandstone, argillaceous rocks (such as shale, slate, phyllites, argillite), greywacke, siltstone, some porous limestone and dolomite aggregates, and porous chert particles are less frost-resistant than the dense crushed stones (e.g., dense limestone, dolomite, granite, quartzite, basalt, diabase, gabbro) or dense siliceous-calcareous gravel aggregates.

Performance of an aggregate during cyclic freezing and thawing is usually evaluated by past performance in the field, and laboratory tests. The latter include ASTM C 666 test for evaluating freeze-thaw resistance of concrete incorporating the aggregates in question, and ASTM C 88 sodium or magnesium sulfate soundness test for evaluating the weathering resistance of aggregate.

Two common types of deteriorations associated with the use of unsound aggregates in concrete exposed to freezing are – **aggregate popout** and **D-cracking**. Particles susceptible to freezing-related damage (i.e., porous, absorptive, low strength, low modulus of elasticity) and/or alkali-silica reactive aggregates cause popouts. Popouts are fragments of unsound near-surface aggregates that have been disintegrated from the concrete surface resulting in shallow, commonly conical depressions on the finished concrete surface (Figure 10). Usually, fractured remains of the unsound aggregate particles are present at the base of the depression. Popouts are formed by: (a) expansion and fracturing of near-surface particles by moisture absorption, freezing at critically saturated conditions, or alkali-silica reaction, and (b) loss of the surface mortar along with a portion of the unsound fractured aggregate particle forming a shallow conical depression on the remaining affected particle at the surface. Deicing salts aggravate popout by increasing the degree of saturation of the near-surface unsound aggregates. Usually, it is the coarse rather than fine aggregate particles having high absorption and porosity (containing many fine to medium-size pores, 0.1 to 5 μ m size) that are easily saturated during wetting cause popouts during freezing. Larger pore spaces in aggregates do not usually saturate as readily as the finer pores and water in very fine pores freeze more readily than water in coarse pores. The potential for popout due to freezing at critically saturated condition usually depends on a critical particle size, above which the potential increases. The critical size depends on the rate of freezing, porosity, permeability, grain-size, pore structure, and tensile strength of the particle; it is higher for coarse-grained particles, or particles having low permeability or disconnected pore structures.

D-cracking (i.e., ‘Deposit-cracking’ – so named due to the frequent occurrences of dark colored deposits of principally calcium carbonate in the cracks) is a common type of freeze-thaw distress along the joints in many concrete pavements. The cracking is a consequence of expansion during freezing of unsound aggregates that are critically saturated. D-cracking usually starts at or near the base of the pavement joints (where water accumulates and saturates the concrete) and migrates upwards. They are mostly closed-spaced fine cracks, oriented parallel to transverse and longitudinal joints that later multiply outward from the joints toward the center of the pavement panel. Over the years of cyclic freezing and thawing, severe disintegration of concrete can occur, where the joints are no longer serviceable. In Ohio, Michigan, Pennsylvania, Indiana, New York, and many other states in the USA that experience cyclic freezing and thawing, the author has detected D-cracking in concrete pavements made using crushed porous carbonate stones and gravel coarse aggregates.

Usually, unsound aggregates having high potential for popouts also show similar high potential for D-cracking. Common strategies to prevent aggregate-popout and D-cracking include: (a) avoiding use of unsound aggregates, (b) controlling the aggregate properties that influence its freeze-thaw durability, (c) beneficiation by adding sound aggregates, (d) effective drainage to reduce the degree of saturation of unsound particles, (e) deep embedding of unsound aggregates into concrete, effective finishing and curing practices, and low water-cementitious materials ratio of surface mortar to prevent moisture saturation of near-surface aggregates to reduce surface popouts, and (f) the protection of concrete surface from moisture saturation by various surface treatments (e.g., applying penetrating or film-forming sealers).

Pozzolan and Cementitious Materials

Incorporation of pozzolanic and supplementary cementitious materials (e.g., fly ash, ground granulated blast furnace slag, silica fume, natural pozzolan, metakaoline, rice husk ash, etc. as partial replacement of portland cement) are known to increase the density, impermeability, and other properties of concrete microstructure by a combined effect of: (a) grain-size refinement (replacement of calcium hydroxide component of portland cement hydration to calcium silicate hydrate by pozzolanic reaction) and (b) pore-size refinement (densification of overall microstructure by filling of capillary pores in the paste and in various interfaces by the calcium silicate hydrate pozzolanic reaction product).

Despite the overall densification of concrete and other well-known advantages of their incorporation, increased scaling potential was reported in some field and laboratory studies on performances of concretes containing fly ash, slag, or silica fume. In fact, there have been conflicting reports in the literature on increased as well as slightly decreased scaling resistance of concretes containing these cementitious materials compared to the ordinary portland cement concrete [7]. Pozzolans usually require adequate curing and extended periods of maturity for the advanced pozzolanic activity, without which a concrete surface may not gain the necessarily benefit of pozzolan-induced densification and moisture tightness. Slow strength gain with some of these materials, lack of maturity prior to freezing, inadequate curing, improper design or construction practices of concrete incorporating such materials, and other factors however, are often found to be the cause for the increased scaling potential rather than the material itself. Pozzolan and supplementary cementitious materials should not increase scaling potential if all other factors mentioned before for the scaling resistance of concrete (e.g., adequate air entrainment, low water-cementitious materials ratio, and proper finishing and curing practices) are satisfied so that the beneficial effects of densification of microstructure by these materials can be utilized for additional scaling resistance. In designing a scaling-resistant concrete, ACI's building code requirements for structural concrete limits fly ash content to 25 percent of total cementitious materials, and ground granulated blast furnace slag to 50 percent of the total.

Literature data on influences of portland cement composition and fineness on scaling resistance of concrete is scarce [7]. The use of finely ground cement (e.g., ASTM C 150 Type III portland cement) are reported to improve the scaling resistance of concrete, which could be due to a combination of faster hydration rates of fine cements, which reduce the risk of scaling at an early age, especially during cold weather construction, and reduction in the average size of capillary pores in the paste when finely ground cements are used [7]. The use of low alkali and low C_3A cements reduce the amount of scaling compare to a concrete containing high alkali or high C_3A cement. Cement alkali content is reported to have an influence on the efficiency of air entraining chemicals, stability of air void system in fresh concrete, and air void spacing factor. Cement content, *per se*, has little influence on scaling resistance; however, reducing the paste content (without affecting the workability) such as by good aggregate grading is certainly beneficial for

scaling resistance since reducing paste content reduces the amount of freezable water and pore spaces in the concrete.

Compressive Strength and Water-Cementitious Materials Ratio

ACI Committees 201, 318, and others have recommended a compressive strength of at least 4000 psi (28 MPa), and a maximum water-cementitious materials ratio (w/cm) of 0.45 for a concrete exposed to cyclic freezing and thawing in a moist environment, or to deicing chemicals. A compressive strength of at least 4000 psi (28 MPa) is desirable for most normal-weight outdoor concrete slabs exposed to freezing. A compressive strength of at least 3000 psi is recommended in a moderate weather regime. Usually, the higher the compressive strength, the denser is the paste, the more resistant it is to moisture saturation, the lesser the amount of freezable water in the paste, and hence, the more resistant the paste is to the distress due to cyclic freezing.

Water-cementitious materials ratio (w/cm) influences the porosity of the paste, both in the bulk paste and at aggregate-paste interfaces, and thereby controls the strength and durability-related properties of concrete, especially at the surface region, and its scaling resistance. Most field and laboratory tests have shown that for normal-strength concretes, scaling resistance increases as w/cm decreases. Water-cementitious materials ratio controls the permeability of paste to moisture by controlling the amount and connectivity of the capillary pores. Permeability of a well-consolidated portland cement paste usually stays very low as long as w/cm is less than 0.45 (i.e., when the capillary pores are not connected); permeability increases rapidly as w/cm increases above 0.45 (due to connectivity of capillary pores and an increase in capillary channels in paste). A maximum ratio of 0.45 is, therefore, recommended for assuring the necessary resistance of paste to moisture penetration. Permeability of paste at the surface region controls the rate at which critical water saturation levels are reached at the surface concrete.

Many specifications on outdoor concrete slabs mention the industry guidelines on the minimum compressive strength requirement without also specifying the maximum w/cm requirement. In author's opinion, specifying the maximum 0.45 w/cm requirement is more important than the strength for improving the scaling resistance of concrete.

High-strength and high performance concretes having water-cementitious materials ratio less than 0.30 are reported to have good scaling resistance (*a la* ASTM C 672 test) and good freeze-thaw durability (*a la* ASTM C 666) regardless of air entrainment [6]. The dense nature of the paste and aggregate-paste interfaces, and the negligible amounts of freezable water in these concretes are responsible for reducing the degree of moisture saturation, and hence, scaling. Entrained air is reported to be necessary for scaling resistance of concrete having a water-cementitious materials ratio greater than 0.30 [6].

Degree of Critical Saturation

A concrete is defined to be "critically saturated" when more than 91 percent of the pore spaces are filled with water so that during freezing of water into ice, expansion associated with 9 percent increase in volume develops hydraulic stresses in the neighboring regions. Therefore, the potential for scaling is high when a concrete is critically saturated and does not have adequate air voids to reduce the stresses from freezing. Air voids reduce freezing-related stresses either by accommodating the water escaped from the freezing front and thereby reducing the hydraulic stresses, and/or by providing room for expansion of water advancing towards the freezing front from non-frozen sites, and thereby reducing the osmotic stresses. Many old, non-air-entrained concrete structures are sometimes reported to have survived cyclic freezing and thawing, which is

due to the fact that the structural element in question was never critically saturated so that no destructive stresses developed from water-to-ice expansion during freezing. Either the structural element in question has had good drainage (e.g., vertically oriented, e.g., columns) where water did not stand and absorbed into concrete, or, the concrete was made using well-graded sound aggregates with minimal amount of dense, water-tight, near-impermeable paste where the amount of evaporable or freezable water was low. Even a poorly air-entrained concrete can survive distress during freezing if it is designed in such a way that it never reach the level of critical saturation prior to or during freezing, so that there will not be enough freezable water present in the concrete to create any disruptive stress.

Due to the hygroscopic nature of salts, application of deicing salts, however, can cause severe scaling, such as in some case studies by the author, where non-air-entrained concrete slabs survived for many years in salt-free conditions, and then scaled during exposure to salts. Petrographic examinations can evaluate the factors that affect the moisture content of paste and aggregates at the surface during freezing, and whether or not scaling is due to the distress related to expansion of a critically saturated poorly air entrained or improperly finished concrete at the surface.

Chemical Admixtures

The use of a chloride-containing set-accelerating admixture is common in cold weather construction for rapid development of strength by accelerated cement hydration before the freezing-related tensile stresses can cause scaling. Addition of chloride, however, increases the risk of corrosion of reinforcing steel in concrete and the degree of saturation of concrete (especially at the surface if chloride migrates towards the top). Therefore, the use of a non-chloride-based set accelerating admixture is preferable (and increasing common).

The use of a set-retarding chemical is common in hot weather construction, which slows down cement hydration and thereby delays the final set. Excessive delay, however, increases the potential for sheet-type scaling if finishing initiates prior to the cessation of bleeding. Increased bleeding due to the use of a set retarding chemical can reduce the durability of surface concrete, especially if finishing operations start while bleed water is present on the surface.

Many chemical admixtures are reported to influence the effectiveness of air entraining chemicals and the resultant air void parameters. Superplasticizers, or high-range water reducing admixtures are reported to cause a time-dependent loss of air content in plastic concrete [8] where the rate of air loss with time is dependent upon the type of superplasticizer being used with an air entraining agent, and coarsening of the air-void system in concrete with an increased air void-spacing factor; however, such coarsening may not affect the freeze-thaw durability of concrete if the use of superplasticizers and low water-cementitious materials ratio in the mixture increase the density and water-tightness of concrete and decrease the amount of freezable water in the concrete [9].

[B] FACTORS RELATED TO CONSTRUCTION PROCEDURES

Mixing, Placement, and Consolidation

Even an adequately air-entrained concrete may not be durable, if it is not mixed, placed, and consolidated properly. Inadequate mixing, or excessive mixing can affect the ultimate air-void system of concrete (sometimes by affecting the influence of some chemical admixtures on the air-entraining agent), and hence its freeze-thaw resistance. Duration of mixing can affect the effectiveness of some air entraining chemicals. Inadequate mixing of batch or tempering water at

the jobsite can affect the ultimate air void system and distribution of air voids in concrete. The possibility of inadequate mixing, and its effect on the air void system of concrete are commonly evaluated by petrographic examinations.

Vibration is the most common method of consolidation, which has a significant influence on the ultimate air content of concrete. Air content usually decreases with increasing vibration duration and/or frequency. Inadequate consolidation leaves excessive entrapped voids around the aggregates (honeycombing) and reduces the strength and moisture-resistance of concrete in the honeycombed areas. Concrete must be properly consolidated to resist any undesirable moisture penetration (and saturation).

Finishing

Improper finishing practices are very common causes of scaling, which can ruin even a good quality, and adequately air-entrained concrete. The three common improper finishing practices, which can reduce the scaling resistance of a concrete include:

- Initiation of finishing operations prior to the cessation of bleeding and, as a result, entrapment of bleed water beneath the prematurely finished surface;
- Softening of the surface by addition of water during finishing, or finishing with bleed water on the surface; and
- Loss of air at the surface and distortion of air voids to the extent of degrading the air-void system of concrete at the surface relative to that in the body, by prolonged finishing.

Figure 7 shows a few case studies related to these factors, which have caused surface scaling in air-entrained concretes. Table 3 (Section 2) provides petrographic observations of these concretes related to finishing improprieties.

Scaling due to Premature Finishing - Rapid top-down stiffening of a slab in a hot, windy, sunny, and dry weather condition may encourage initiation of finishing operations prior to cessation of bleeding. Such environmental conditions create a stiffened, “crusty” surface without any bleed water sheen on the surface (common in fall and spring). The surface may appear ready for finishing while the concrete may still continue bleeding inside; bleed water accumulates beneath the crusted surface and eventually creates a thin plane of weakness immediately beneath the surface, which is susceptible to scale during freezing, or simply by traffic load even in a non-freezing environment. This is common when the rate of evaporation of surface water is higher than the rate of bleeding, which can also cause crazing and plastic shrinkage cracking. Besides the weather condition (i.e., high wind, hot air, low relative humidity, direct sun), top-down stiffening can also occur when a slab is too thick with big temperature and 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. Common industry recommendation is not to initiate finishing until the footprint impression on the surface to be finished is less than $\frac{1}{4}$ in.

Factors that reduce bleeding rate, bleeding capacity, and extend bleeding duration and initial set are susceptible to increase the potential for premature finishing. These factors are: (a) placement of a slab on a cold, non-absorptive subbase (which increases bleeding capacity and duration); (b) high air temperature (which decreases the time of setting, bleeding rate and duration); (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); and (f) use of set-retarding chemicals especially in cold weather (which retard setting and prolong bleeding). All these factors can create a situation, where finishing operations may start prior to the cessation of bleeding.

Petrographic examinations can diagnose many of these factors, and their relative roles in causing any bleed water entrapment, and subsequent scaling of the finished surface (Figure 7, and Table 3 Section 2). Usually, the concrete surface shows thin sheet-like masses of scaled pieces (having a more or less uniform nominal thickness of $1/16$ to $1/4$ in.) loosely adhered to the main body of concrete with a discontinuous and yet distinct “gap” between the thin sheet-like scaled surface and the main body of concrete beneath. The loose, scaled pieces on the distressed surface may occur at isolated locations or may cover a large area. The texture of the undersides of “scales” shows evidence of bleed water entrapment and intersected bleed water channels, along with soft paste and many coarse aggregate sockets. The initial plane of weakness develops by bleed water accumulation beneath the finished surface, where bleed water eventually dries out and creates a “gap”. Later, accumulation of water in these preexisting gaps between the incipient scales and the main body of concrete, such as during exposures to rain or salts (which increases the degree of saturation of concrete) causes expansion during freezing, and subsequent sheet-like scaling of the finished surface. Even in regions without freezing, simple traffic loads can cause scaling of these sheet-like masses of the finished surface.

Scaling due to softening of the surface by finishing in the presence of excess water - Finishing operations on a surface containing excess water, either from water added during finishing to improve workability, or, the bleed water sheen on the surface that has not been evaporated out before finishing can cause mixing of that excess water back into the surface mortar and, a consequent increase of water-cementitious materials ratio at the surface, and subsequent reductions in hardness, strength, water-impermeability, and scaling and abrasion resistance of the surface concrete. Addition of excess water: (a) reduces the compressive strength of surface concrete, which is needed to resist the freezing-related stresses and (b) increases permeability of surface mortar, which reduces the protection of any unsound aggregate particles situated immediately beneath the finished surface. Any such operations inevitably reduce the scaling resistance of the surface, especially if the surface is exposed to deicing salts. Petrographic examinations diagnose a significantly higher water-cementitious material ratio at the surface region compared to that in the body and associated textural, compositional, and mineralogical changes in the surface region as a result of the presence of “excess” water (Table 3). Use of a mid-range water reducer is beneficial to maintain a good workability of concrete during finishing without addition of excess water.

Scaling due to prolonged finishing operations – Sometimes, to achieve an acceptable finished texture and appearance of a surface, finishing operations may continue beyond the “window of finishability” (which, usually, is the period between the initial and final set of concrete). Such over-finishing, or prolonged finishing operations usually reduce the air content of air-entrained concrete at the top $1/16$ to 1 in. depth compared to that in the body, depending on the duration and the pressure applied during finishing, largely by removing the coarse air voids, and sometimes show distorted (oval-shaped) air voids at the surface region. Being sticky in nature, an air-entrained concrete usually increases the difficulty in achieving a desirable finish, which, along with many other factors can prolong the finishing duration. This does not necessarily affect the scaling resistance of the surface as long as the air loss is limited to the loss of the large air voids without affecting the finer bubbles so that the surface air void system has adequate specific surface and acceptable void spacing factor (especially the latter parameter, which is most

important for freeze-thaw durability). Over-finishing, if significantly reduces the air content at the surface or increases the air void spacing factor, can reduce the scaling resistance of surface even if the interior concrete has a good air void system. According to Mielenz [10] “air content in the uppermost part of a concrete slab, particularly within $\frac{1}{2}$ inch of the finished surface, is characteristically less than that in the concrete at greater depth because the manipulation removes a large portion of the larger voids. This action may decrease the air-void content of the topmost $\frac{1}{16}$ inch to one-third or less of the air content of the concrete as a whole. Nevertheless, if the concrete was originally adequately air-entrained, the spacing factor is not significantly modified.” Later, based on experimental work, Newlon [11] concurred with Mielenz by stating that “the changes in the air-void system indicate that the volume of air is reduced, but that the air lost is in the form of larger bubbles, which offer little protection. The more important void properties, specific surface, and spacing factor are improved.” Prolonged finishing also densifies the surface mortar, which can be beneficial for improving the moisture impermeability of the surface and scaling resistance. Case studies by the author [4] have shown that prolonged finishing operations have both: (a) improved the scaling resistance of concrete in cases where such operations densified the surface region and yet did not increase the void spacing factor of the surface air void system compared to that in the body, and (b) increased the scaling potential in other cases where besides finishing-induced air loss and void shape distortion, the overall air void system became coarse with wide void spacing, and the surface has been exposed to deicing salts. A detailed air void analysis of concrete, especially at the surface region (at the top 1 to $1\frac{1}{2}$ in. depth) can detect whether or not finishing-induced loss of large air voids and distortion of void shapes have reduced the scaling resistance of concrete by “coarsening” the air-void system at the surface.

Curing

Curing is the process by which concrete matures and develops hardened properties over time as a result of continued hydration of the cement in the presence of sufficient water and temperature. Curing prevents the loss of moisture from the concrete surface (especially in a hot, windy, or dry weather condition), supplies the necessary moisture, and maintains a favorable concrete temperature for a sufficient period of time so that the surface develops adequate durability by reducing the porosity by the necessary hydration of cement particles at the surface. Therefore, curing has a significant influence on the scaling resistance of surface, especially in the presence of deicing chemicals. Durability of a good quality, properly placed, and finished concrete cannot be ensured unless it is adequately cured. Many desirable properties of concrete for scaling resistance, especially at the surface region (which is most susceptible to freezing, salt exposure, and scaling), are improved by curing. Therefore, curing should be initiated immediately after finishing, and should be extended for adequate periods. The duration of curing depends on the composition and properties of the concrete mixture, the water-cementitious materials ratio, and the rate of development of the desirable properties (e.g., strength) during and after curing. For concrete slab-on-grade and structural concrete, the length of the curing period for ambient temperatures above 40°F should be at least seven days, or the time necessary to attain 70 percent of the specified compressive strength (as long as after curing the concrete develops 100% of the specified strength within the required time period [12, 13, 14].

Curing assures adequate hydration of portland cement particles at the surface, so that the surface can develop the necessary strength, density, hardness, and moisture-tightness to resist moisture saturation before freezing [14]. Ideally, curing should start immediately after finishing and the final set of concrete. Sometimes, however, an initial curing is needed by fogging, or using liquid evaporation reducers anytime between placement and final finishing of concrete (e.g., in a low-bleeding mix or in an aggressively evaporative environment, or both [13, 14] to reduce the surface moisture loss (e.g., situations where finishing does not start immediately after the

disappearance of the bleed water sheen from the surface). An “intermediate curing” by using a liquid membrane-forming cueing compound is needed after the finishing, but before the final set of concrete, which occurs when the desired surface-finish is rapidly achieved, or setting is delayed, or both [13]. The final curing after the final finishing and final set of concrete employs various methods such as: (a) moist curing by using a wet covering (wet burlap), sprinkling water, ponding, fog spraying, or (b) by using a plastic film to protect loss of moisture from the surface, or (c) by using various spray-applied, liquid membrane-forming curing compounds in compliance with ASTM C 309 or C 1315 [13]. Concretes cured with membrane-forming curing compounds are sometimes reported to show better scaling resistance than similar moisture-cured concretes. Inadequate curing during rapid evaporation of surface water in hot, windy, sunny, and dry weather severely restricts the cement hydration, slows down the rate of strength gain at surface, makes the surface soft and porous, increases the depth of carbonation, increases permeability, potential for plastic shrinkage cracking, and decreases the ultimate scaling and abrasion-resistance of the surface. Cold weather construction usually requires an extended period of curing due to slower rate of cement hydration at the surface than a hot weather construction. Use of a set-accelerating admixture is therefore common in cold weather construction to accelerate the strength development at the surface.

Interaction of atmospheric carbon dioxide with the cement hydration products at the surface region of concrete causes carbonation, which usually confines to within the first few millimeters of concrete beneath the surface. Carbonation usually densifies the surface by filling the pore spaces with calcium carbonate, which is beneficial to the scaling resistance. Excessive carbonation, especially in a poorly consolidated and/or inadequately cured concrete, however, softens the surface, which is detrimental to the scaling resistance. Inadequate curing creates a thin layer of soft, dusty, carbonated surface susceptible to scale, which sometimes forms above a thin, carbonated densified band in the surface region. Adequate curing restricts the carbonation depth and formation of any soft, dusty film by densification of the surface with adequate cement hydration.

Petrographic examinations can evaluate the degree of curing of concrete at the surface and, more importantly, if inadequate curing has reduced the scaling resistance of concrete. An inadequately cured concrete often show a soft, carbonated, sometimes dusty surface having a higher abundance of incompletely or minimally hydrated cement particles at and near the surface region compared to that in the body, which would otherwise hydrate if adequate moisture were present. If an inadequately cured concrete surface is exposed to cyclic freezing at saturated conditions, it does not have the necessary strength to resist the tensile stresses due to freezing of water in pores, and therefore, it scales by softening, crumbling, and disintegration. Deicing salts aggravate surface disintegration because salt-induced increased saturation of the inadequately cured, porous surface increases the tensile stresses during freezing, which could not be resisted by the low strength of the surface-concrete. Poor curing does not cause “sheet-type” scaling of the finished surface (which is common due to premature finishing) but crumbling, increased depth of carbonation, softening, and disintegration of the surface region of concrete. Sometimes, poor curing forms a thin, dense, semi-impermeable zone of carbonated cementitious matrix immediately beneath the surface that separates the soft, porous, and scale-prone surface-mortar from the relatively denser concrete in the interior [15].

Hot and Cold Weather Protections

When a concrete is placed in a hot weather, the risk of rapid drying in warm, arid, and windy conditions increases. When a concrete is placed during cold weather, the following risks are increased: frost damage due to freezing water in the pores in the plastic state, a slow rate of

strength gain due to a slow rate of cement hydration, frost bite before the attainment of maturity, rapid evaporation of surface water (plastic shrinkage cracking), and possible cracking by a rapid drop in temperature and rapid drying after the removal of cold weather protection at the end of the curing. In most of the case studies of the author on scaling of structures placed in cold weather, plastic freezing, exposure to snow and salt prior to the attainment of maturity, and slow strength-gain due to slow rate of cement hydration are found to be the major causes. In such cases, adequate curing, use of high early strength cement, a set-accelerating admixture, a higher strength concrete, or a combination of one of many of these factors are helpful.

ACI Committees' 305 and 306 reports on hot and cold weather construction, respectively, provide several precautionary measures, which should be exercised for protecting concrete from the ambient temperature extremes. Unless the appropriate precautions and curing procedures are taken against the weather extremes, the surface region of the concrete may lose the necessary scaling resistance.

Placement of concrete in summer usually provides time for adequate cement hydration, internal drying, and adequate strength and maturity development prior to the exposure to freezing than a late autumn and winter placement. Winter placement can increase the potential for scaling, especially in the presence of deicing salts, if the concrete is not matured, or properly air-entrained. Adequate cold weather precautions in design, materials selection, proportioning, and construction practices are, therefore, necessary for scaling resistance. Case studies on scaling by the author spans over both hot and cold weather seasons, and there is no indication of increased reports of scaling during the cold weather.

Mortar Lift-off

A common but often misdiagnosed type of surface distress is mortar lift-off, which is described in many literatures as mortar flaking or popoffs (Figures 8 and 9). The author prefers the term 'lift-off' rather than 'flaking' because it indicates a mechanism whereby a small isolated thin finished surface mortar (usually less than $\frac{1}{8}$ in. in thickness) lifts or pops off from above the flat, topsides of near-surface aggregate particles (rather than thin, flake-like peeling of the surface). Inadequate embedding of the near-surface coarse aggregate particles, or the presence of many flat aggregate particles near the finished surface are often mentioned as the causes of the mortar lift-offs. The author, however, encountered many situations where no sign of mortar lift-off was found in concrete slabs having inadequately embedded flat coarse aggregate particles near the finished surface.

It is the author's opinion that mortar lift-off is the result of the presence of a weak bond between the surface mortar and the underlying aggregate particle, which causes a relatively easy lift-off of the finished surface mortar from above the flat, top side of coarse aggregate particles. The weak bond can develop due to one or a combination of the following mechanisms:

- (a) Inadequate curing of the surface, or its early stiffening in a hot, sunny, and windy day where near-surface coarse aggregate particles block the upwelling bleed water from reaching the surface and hydrating the surface cement particles; evaporation of surface water creates a soft surface mortar that is weakly adhered to the aggregate particle and subsequently lifted off;
- (b) Drying shrinkage of surface mortar above the aggregate particle due to evaporation of surface water;

- (c) Mechanical agitations due to continuous finishing operations that reduces the bond between the thin surface mortar and the near-surface flat topsides of coarse aggregate particle; and/or
- (d) Differential volume changes between the near-surface aggregate and overlying air-entrained paste during freezing, where the saturated aggregate expands whereas the paste contracts during freezing, and, thereby, weakens the aggregate-paste bond.

The weak bond between the finished surface and the underlying coarse aggregate particle causes the lift-off of the surface mortar by the traffic load or by freezing of water present at the interface between the thin sheet of surface mortar and the underlying aggregate particle. Portions of the mortar in between the aggregate particles stay unaffected, and so does the aggregate particles present at the sites of the lift-offs. The aggregate particles, which are not usually not fractured, or responsible for the distress in any way, became exposed as a result of the mortar lift-off and may apparently resemble aggregate popouts.

Therefore, mortar lift-off is often misdiagnosed with the more common problems of aggregate popouts in the field [16]. Unlike mortar lift-off, where the exposed aggregate particles are not responsible for the distress, in aggregate popout the near-surface aggregate particle itself is unsound (porous, absorptive, low strength), reactive, or contain deleterious contaminant to cause expansion during moisture absorption and/or freezing at saturated condition. One reason for such confusion is their visual resemblance after prolonged weathering, and often close occurrence in the field. Proper diagnosis by petrographic examinations is essential to determine if the distress is mortar-lift, aggregate popout, or both, and therefore, related to construction defects, use of unsound aggregates, or both, respectively. Mortar lift-off is a result of improper finishing manipulations and/or inadequate curing of the concrete surface, both of which are indicative of poor workmanship. Aggregate popout, on the other hand, is entirely an aggregate-related problem. In mortar lift-off, the exposed aggregate particle is benign but in aggregate popout, the exposed and fractured aggregate particles are solely responsible for the distress.

Drainage

Proper drainage of water is essential for preventing concrete from saturation. Inadequate drainage causes localized ponding in low spots and saturation of concrete at those locations prior to freezing. A saturated concrete is more susceptible to scaling than a dry concrete. Therefore, scaling preferentially starts at the low spot locations, where water ponds. Due to excellent drainage, vertical structural elements (columns and walls) are less susceptible to scaling (even the ones made using nonair-entrained or poorly air-entrained concretes) than the horizontal slabs (e.g., slab-on-grade, decks, pavements, sidewalks, beams). Concentrations of scaling and D-cracking adjacent to the joints are indicative of a higher degree of saturation of concrete along the joints than in portions away from the joints. Good drainage is therefore essential at the pavement joints to reduce the level of moisture saturation in the unsound aggregates.

Surface Treatments

Application of a clear, film-forming, or a penetrating-type surface sealer after curing, or a cure-seal compound after finishing are surface treatments sometimes recommended to protect concrete from cyclic freezing and thawing, and ingress of deicing chemicals, especially during cold-weather construction, or in a scaled concrete slab having a poor air-void system. Surface sealers generally prevent ingress of chloride into concrete and, thereby, reduce the risk of corrosion of reinforcing steel in concrete. Such treatments are often reported to reduce moisture absorption,

thereby increasing the scaling-resistance of the concrete. Sealers resist water and salt penetration by forming a water-repellant surface while allowing the concrete to breathe. Common film-forming sealers are acrylic or epoxy-based systems, which form a thin-film (usually less than 10 mils) on the surface and bond to the concrete. Penetrating sealers are silanes, siloxanes, blended silane plus siloxane, silicates, or siliconates, water or solvent-based products, which penetrate into the concrete surface, usually react with the portland cement hydration products, form a water-repellant, impervious layer at the surface and, thereby, prevent penetration of chloride and moisture into concrete. Penetrating sealers are usually applied after the concrete surface is cured, dry, and hardened, usually after 28 days.

Many sealers and cure-seal compounds, however, may not provide the absolute protection, especially from salts at an early age if they do not bond strongly to the concrete due to improper application, or application on an improper surface having a thin, soft film of laitance, dust, oil, grease, or curing compound, or debond due to freezing of moisture entrapped beneath an impervious film-forming sealer. In such cases, sealer peels off, and concrete may scale and show other distress such as surface-parallel microcracking, or aggregate popout even after the application of sealers. The resistance of a sealer to salt and scaling can be evaluated by cyclic freezing and thawing (*a la* ASTM C 666), salt-scaling resistance (*a la* ASTM C 672), and water absorption tests (*a la* ASTM C 642) on laboratory-prepared or field concrete samples to which sealers are applied according to the manufacturers' recommendations. Performance of a sealer depends on proper surface preparation, weather condition during application, type of sealer, and proper installation procedures. There are, however, conflicting reports from laboratory tests and field evidence on the performance of some sealers on the durability of concrete in cyclic freezing and deicing exposures [7, 22]. Some sealer-treated concretes show improved, similar, or even reduced performance as opposed to the companion untreated concretes. It appears that proper air entrainment, finishing, and curing provide far better protection to concrete against scaling than a surface treatment. Surface treatment is recommended for additional protection, especially if the concrete lacks proper air entrainment, or has other deficiencies related to finishing or curing.

[C] FACTORS RELATED TO CONCRETE MATURITY AND EXPOSURE TO SALTS

Maturity

Maturity is indicated by a compressive strength of at least 4000 psi (28 MPa), and a period of air-drying after curing. For scaling resistance, a concrete must be matured so that it can withstand the distress during freezing. The strength requirement is needed to resist the tensile stresses that develop during freezing of water in the concrete. The drying requirement is needed for minimizing the amount of freezable water in the concrete. Concrete placed in the spring and summer gets enough time to dry and gain strength in the normal course of aging before the onset of winter, and does not require any special treatment. Concrete placed in cold weather (in late fall, winter, or early spring), however, may not reach the maturity, and hence, should not be exposed to salt in the first year. It should preferably be protected by the application of a cure-seal compound immediately after finishing, or by a film-forming or penetrating type surface sealer after curing. The common industry warning of a one-year waiting period before the salt exposure may not be necessary for a good quality and properly constructed concrete placed in spring or summer, but may be judicious for concrete placed immediately before or during cold weather. If salt application is necessary, waiting at least 30 days for air-drying after curing is preferred. The duration of waiting, however, is irrelevant for a poorly air-entrained or poorly constructed concrete, which will scale even if it is exposed to salt after many years of service [17].

De-icing Chemicals

Deicing salts are the most common “alleged” cause of concrete surface scaling. Salts undoubtedly increase severity of scaling in a poor quality, improperly constructed, or “young” concrete. The hygroscopic (moisture-absorbing) properties of salts keep concrete saturated and increase the potential for scaling, but a good quality, air-entrained concrete, properly finished, cured, and matured can resist the effects of many common deicers, such as sodium or calcium chloride based salts. Occurrence of scaling along the roadside edge of a sidewalk or driveway is a common indication of the effect of the splashing of road salts in causing the distress. This is more common during cold weather construction, when concrete does not get enough time to attain the necessary maturity before exposure to salt, and is not protected by a surface sealer. Salt manufacturers often provide warnings on the salt bags for not applying salts during the first year of construction; literature reports of this so-called “waiting period” vary from a few months to as long as 5-10 years [18].

For public safety reasons, in many areas, deicing salts must be used, such as on sidewalks, walkways, pavements, driveways, and other outdoor slabs in residential and commercial buildings (e.g., schools, hospitals, and other public places). As mentioned, deicing salts do intensify the severity of scaling, and many outdoor slabs did show sound condition for years until salt was applied, but the immediate claim on salts as the sole player for scaling is not justifiable, especially if salt was applied to a poor quality, improperly constructed concrete, or to a concrete at an early age prior to its maturity. In all these cases, concretes lack the necessary quality for adequate protection against the deleterious effects of salts. *There are numerous examples of sound concrete slabs, which have been exposed to deicing salts for many years with no problem, as well as many scaled slabs, which have never been exposed to salts.* Effects of salts on concrete scaling is most pronounced if: (a) the concrete is non-air-entrained, or inadequately air-entrained, (b) inadequately finished and/or cured, (c) not matured, or (d) has been exposed to corrosive salts, which are known to decompose the portland cement hydration products.

In a pioneering laboratory study in 1956 on salt scaling of concrete, Verbeck and Klieger [18] demonstrated that: (a) an air-entrained concrete shows a much better resistance to deicer scaling than a non-air-entrained concrete; (b) maximum scaling usually occurs at a low deicer concentration, in the order of 2 to 4 weight percent than at higher concentrations, or the absence of deicer; (c) the mechanism of scaling by calcium or sodium chloride based deicer is primarily physical rather than chemical, and related to the built up of osmotic and hydraulic pressures exceeding the normal hydraulic pressures from freezing of water in paste; (d) no scaling was observed in their study in the laboratory scaling test for concrete surface, which had no free water on it during freezing; and (e) a period of air drying after curing and prior to freezing greatly increased the resistance of concrete to surface scaling. All these findings, obtained 50 years ago, remain valid for designing a modern scale-resistant concrete.

Common deicing chemicals with progressively increasing severity on concrete are sodium chloride, calcium chloride, magnesium chloride, urea, potassium chloride, and ammonium sulfate/nitrate.

Sodium and calcium chloride are the most common types of deicing salts. As mentioned before, the primary actions of these deicers are physical in nature related to the build up of osmotic and hydraulic pressures in the paste, exceeding the normal hydraulic pressures from freezing of water in concrete. The hygroscopic properties of salts attract water, and keep concrete saturated in between the wetting/thawing cycles, increase the frequency of freezing and thawing cycles and, thereby, increase the potential and severity of scaling. Besides these well-known physical (i.e.,

hydraulic and osmotic) actions of salts on concrete, there are, however, a few theories about deleterious chemical actions of these salts on concrete. According to some researchers, a sodium chloride solution can cause softening and increased porosity of paste by dissolution of calcium hydroxide component of portland cement hydration [19]. Calcium chloride is mentioned by some researchers to cause scaling by disruptive hydraulic pressure associated with expansive formation of calcium oxychloride ($3\text{CaO}\cdot\text{CaCl}_2\cdot 15\text{H}_2\text{O}$) by reaction of calcium chloride with the calcium hydroxide component of portland cement hydration; use of pozzolanic materials to reduce the calcium hydroxide content in the paste is, therefore, suggested as a mean of controlling the chemical damaging action of calcium chloride [20].

Magnesium chloride is well-known in causing chemical attack and softening of paste by decomposition of the calcium hydroxide component of portland cement hydration into magnesium hydroxide (brucite), and, more importantly, decomposition of calcium-silicate hydrate – the main cementitious component of portland cement concrete into magnesium silicate hydrate, which is a soft compound having no cementitious property [21]. Usually, formation of an insoluble brucite coat on the surface tends to protect the underlying concrete from further ingress of magnesium chloride, unless the coating is continuously or intermittently washed away by the migrating salt solution and exposes the fresh interior concrete for further attack.

Similar to the magnesium-based salts, ammonium sulfate and ammonium nitrate are also known to cause severe scaling (more scaling than sodium or calcium chloride deicers), partially by chemical reactions and decomposition of the paste. In such cases, scaling can occur even in a properly air-entrained, good quality, and well-constructed concrete.

Unless exposed to a corrosive salt, use of a properly air-entrained, dense, good quality concrete, which is properly placed, finished, cured, and matured are the best defense against the deleterious actions of common sodium and/or calcium chloride-based deicing salts.

Salt Hydration Distress – A Mechanism of Concrete Scaling in an Environment of Soluble Salts and Cyclic Wetting and Drying

The term “salt hydration distress” is coined by Hime et al. [23] to describe a special type of concrete or masonry surface scaling or spalling due to exposure to soluble salts having phases that readily transform between anhydrous (or less hydrous state) and hydrous states during cyclic wetting and drying. The distress is a result of expansions due to the repeated conversions of soluble salts from their anhydrous (or less hydrous) to hydrous states due to daily fluctuations in temperature and/or relative humidity. A common example is scaling due to reversible transformations of sodium sulfate salts, i.e., thenardite (Na_2SO_4) to mirabilite ($\text{Na}_2\text{SO}_4\cdot 10\text{H}_2\text{O}$) during cyclic wetting and drying. The thenardite-to-mirabilite conversion is accompanied by an astonishing 315 percent increase in situ solid volume, which is the main reason for concrete or masonry surface scaling [23, 24].

Phase transformations similar to the thenardite-mirabilite hydration include: (1) thermonatrite ($\text{Na}_2\text{CO}_3\cdot \text{H}_2\text{O}$) to natron ($\text{Na}_2\text{CO}_3\cdot 10\text{H}_2\text{O}$), which is accompanied by a 261 percent solid volume increase, and (2) thermonatrite to sodium carbonate hepta-hydrate form ($\text{Na}_2\text{CO}_3\cdot 7\text{H}_2\text{O}$), which is accompanied by a 179 percent solid volume increase. Table 3 (Section 5) lists hydration reactions of various salts, which can cause surface distress. In all these reactions, the total volumes of hydration products are lower than that of the reactants (i.e., anhydrous salts + water). It is, however, the significant increase in solid volumes of the final solid hydrated phases compared to that of the anhydrous (or less hydrous), which is responsible for the distress (water finds its way to the reaction sites through interconnected capillary pores and microcracks). The

requirements for salt hydration distress are, therefore, the presence of: (1) highly soluble salts; (2) exposure to a cyclic wetting and drying environment; and (3) reversible transformations of the salts between different hydration states, due to variations in ambient temperature and humidity.

The physical aspects of the thenardite-to-mirabilite transformation mechanism, however, are somewhat difficult to interpret because of their high solubility in water. Unlike the hydration of free lime, which takes place *in situ* at the surface of the free lime, hydration of thenardite to mirabilite may be *in situ*, or, through solution, or both. Additionally, if mirabilite is initially formed, when it converts to thenardite (which occupies a smaller volume) additional solutions will create new deposits to fill the vacated space so that subsequent conversions to mirabilite will have less space in which to form and enhance the magnitude of the stress. For this to occur, the process must take place within the concrete. Hence, efflorescence, which, by definition, is a surface deposit, does no harm, which often is the case, but is an indicator of possible salt hydration distress that merits deeper investigation.

Concrete Scaling Due to Zeolite (Leonhardite-to-Laumontite) Transitions – The reversible transformations of laumontite, and its partially dehydrated brother leonhardite are mentioned in ASTM C 294 as contributors to scaling because of their volume changes upon wetting and drying [24]. Leonhardite is a family of several dehydrated forms of laumontite produced by drying. The general formula for laumontite is $\text{Ca}_4[(\text{AlO}_2)_8(\text{SiO}_2)_{16}]\cdot 16\text{-}18\text{H}_2\text{O}$ – leonhardite can have 12 or 14 H_2O (sodium and potassium can substitute for some of the calcium). The differences in solid volumes of the different hydration products are difficult to determine because of the lack of density data for the several forms of leonhardite. However, based upon calculations using unit cell dimensions, the change in solid volume is in the range of 3 to 6 percent depending on its hydration state and calcium-alkali ratio. Although the volume changes are not as large as the sodium sulfate/carbonate salts, they are sufficient to cause popouts and scaling in concrete. Zeolites are usually the alteration products of feldspars, and in the case of altered granite, zeolites are associated with other rock components, such as quartz, unaltered feldspars, mafic minerals, and mica. The laumontite-leonhardite transformations cause the particles in which they are present to crumble and powder. In turn, concrete flanking the particles crack (Figure 11). Because the wetting and drying occurs at the concrete surface in contact to ambient temperature and moisture, thermal and moisture fronts move in and out of the surface region of the concrete (similar to a freezing isotherm that causes scaling) causing cyclic transformations of laumontite to leonhardite so that distress occurs in line (parallel) with the front – hence, the distress occurs as scales, a look-a-like to scaling due to cyclic freezing and thawing.

CONCLUSION

Improper concrete materials and/or proportioning (e.g., air entrainment, *w/cm*), improper/inadequate construction (e.g., finishing, curing) practices, inadequate concrete maturity, and exposure to corrosive deicing salts can cause scaling, either individually, or in combination. The degree of scaling depends on the relative roles of these factors in the complex interplay of all factors that cumulatively control the ultimate scaling resistance of concrete. The effects of salts, the commonly blamed culprit for scaling, are most prominent in a poor quality concrete (having a poor air-void system, unsound aggregate, or low strength), improperly constructed concrete (improperly consolidated, finished, cured, or designed concrete), or in a premature concrete that has not attained the necessary maturity prior to the first exposure to salt. A surface treatment is temporarily beneficial, especially in a poor quality concrete, or in a slab placed during cold weather; but it does not waive the first-hand requirements of proper placement, finishing, and curing practices of a good, air-entrained concrete, especially for its long-term durability and scaling resistance.

During investigation of concrete scaling, a holistic approach involving condition survey, review of all relevant background information of the project, and detailed laboratory examinations are needed to evaluate the potential roles of all the above-mentioned factors on scaling.

The article ends by providing a few general guidelines for creating a scale-resistant concrete:

1. Use air-entrained concrete having a good air-void system consisting of numerous, uniformly distributed, fine, close-spaced entrained air voids. The air content should conform to design or industry recommendations. More importantly, the specific surface of the air-void system should be at least $600 \text{ in}^2/\text{in}^3$ ($23.6 \text{ mm}^2/\text{mm}^3$); and the maximum void-spacing factor should be 0.008 in. (0.2 mm)
2. Use well-graded, well-distributed, sound, frost-resistant aggregates conforming to the specifications of ASTM C 33. Control the effects of properties of aggregates by various means, which decrease the scaling resistance of aggregates.
3. Use a concrete mixture having a maximum water-cementitious materials ratio of 0.45 and a 28-day compressive strength of at least 4000 psi (at least 3000 psi for concrete in moderate exposures). In the concrete mixture design, specify not only this strength requirement but also the maximum water-cementitious materials ratio requirement.
4. Follow good concrete placement, consolidation, and finishing operations. Do not start finishing prior to the cessation of bleeding. Do not add water during finishing that can have an adverse effect on the properties of hardened concrete at the surface. Do not initiate finishing while the bleed water is present on the surface. Avoid prolonged finishing operations, which can affect the air void system at the surface.
5. Provide adequate curing of concrete immediately after finishing for creating a dense, low-permeable surface of good durability.
6. Concrete must be matured prior to the first exposure to cold weather, and salts. Concrete should attain a compressive strength of at least 4000 psi and a period of air-drying. If possible, try to avoid using salts at the first year, especially if the concrete is placed during cold weather, or immediately prior to the cold season, and is not protected by a surface sealer.
7. Salts should not be used if the concrete is poorly air entrained, non-air-entrained, improperly finished, or not matured due to placement during, or immediately prior to a cold weather. Under these situations salt would aggravate scaling; and, therefore, placement of a surface sealer would be beneficial.
8. Irrespective of concrete quality or construction methods, certain corrosive salts, such as magnesium chloride, potassium chloride, ammonium sulfate, and ammonium nitrate based deicers can cause chemical attacks in paste and subsequent scaling by chemical decomposition of the portland cement hydration products in the surface concrete.
9. Provide adequate drainage to prevent moisture saturation of concrete and unsound aggregates.
10. Provide adequate precautions during hot and cold weather constructions, according to the recommendations provided by the ACI Committees 305R and 306R, respectively.

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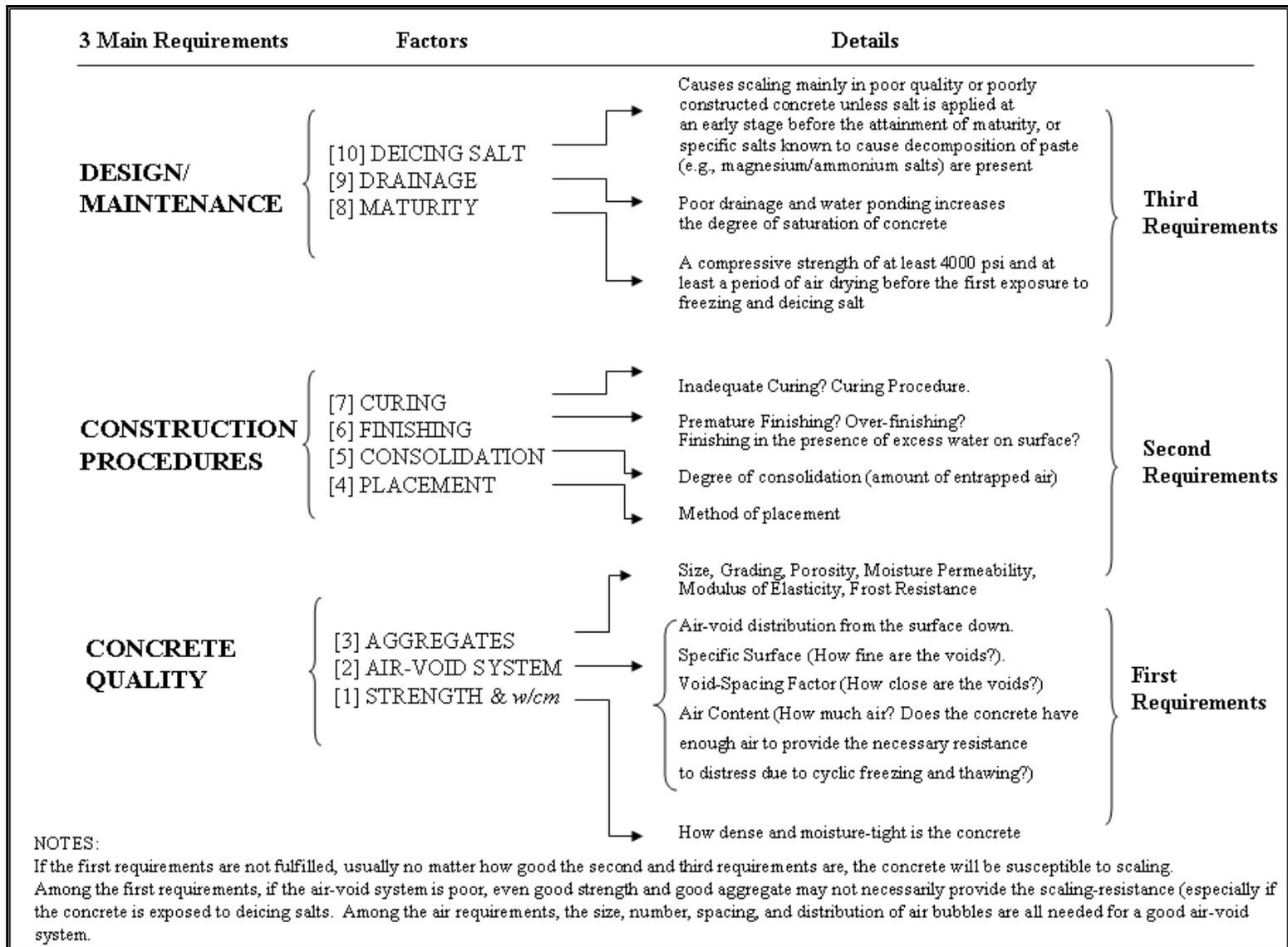


Table 1: Factors that can contribute to concrete surface scaling – A holistic Approach. Shown are ten common factors, categorized into concrete materials, construction practices, and design plus maintenance, which should be considered for designing a scale-resistant concrete.

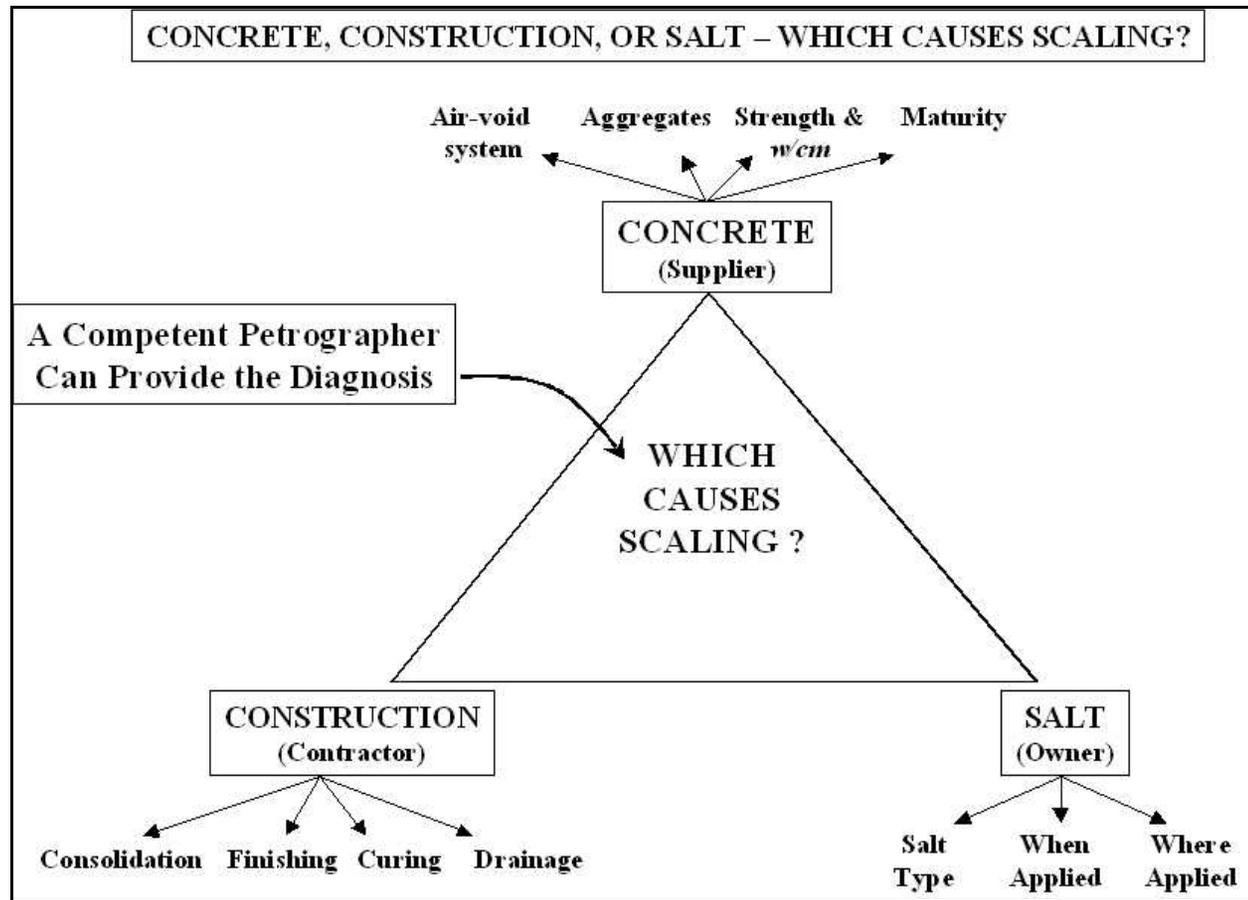


Figure 1: A holistic approach to concrete scaling. Shown are the factors that are important to produce a scale-resistant concrete. A poor quality concrete, improperly constructed concrete, a concrete exposed to salts at an early age, and applications of salt on a poor quality and/or poorly constructed concrete can cause scaling.

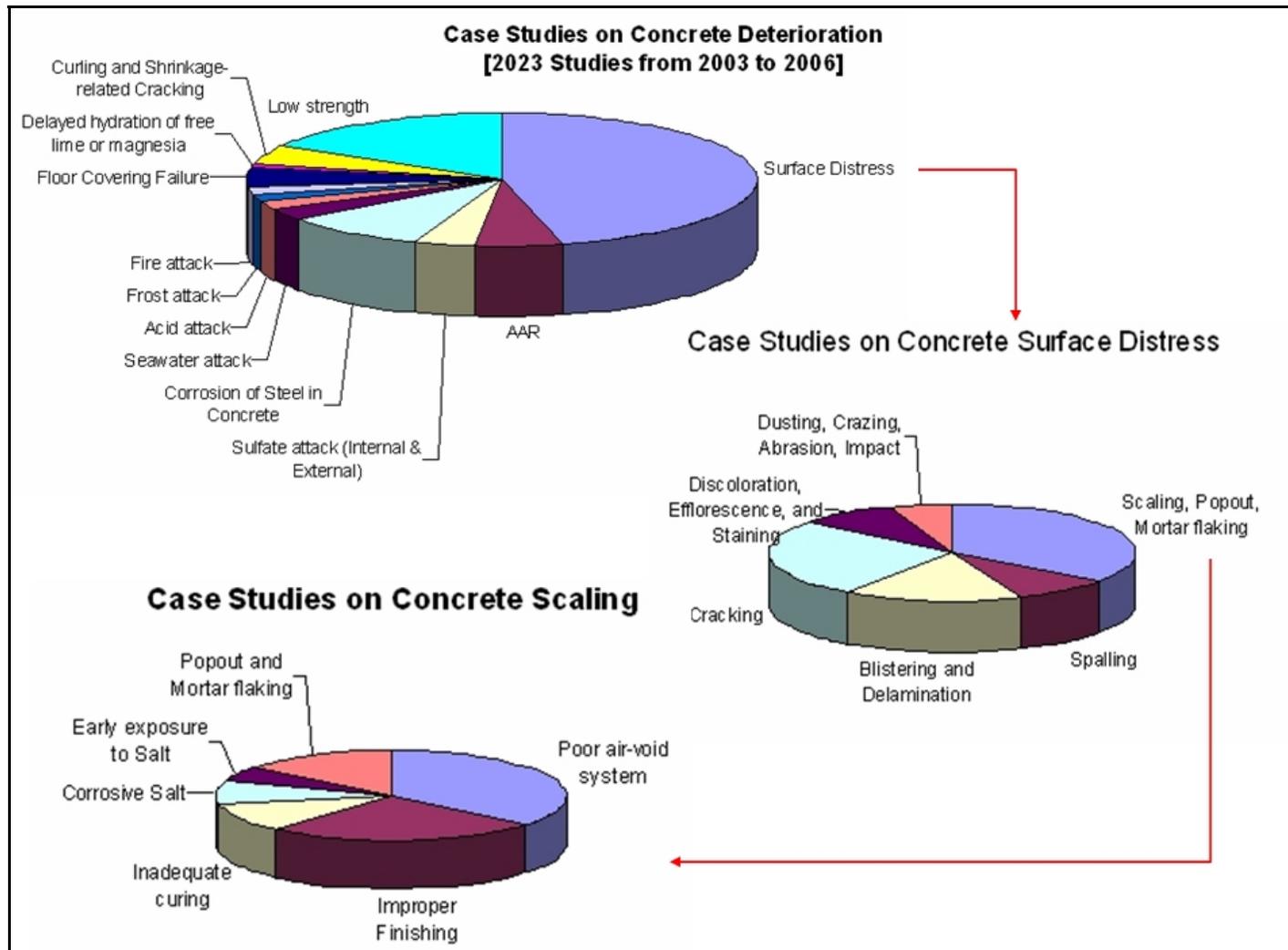


Figure 2: Case studies on concrete deterioration conducted by the author over a period of three years. Studies involving surface distress outranked all other types. Among the surface distress-related studies, cases dealing with surface scaling and associated distresses are the most common types. Among the scaling-related cases, the most common causes of scaling are found to be poor air void system and improper finishing/curing practices. Scaling by corrosive salts, or early exposure to salts are of found to be lesser occurrences than that related to concrete materials and workmanship.

Nominal Maximum Aggregate Size, in.(mm)	Air Content (percent)		
	ACI 201.2R, ACI 211.1, ACI 318, ACI 345R, ASTM C 94	ACI 301	
	Severe Exposure	Moderate Exposure	Destructive Exposure
3/8 (9.5)	7½	6	6 – 10
½ (12.5)	7	5½	5 – 9
¾ (19.0)	6	5	4 – 8
1 (25.0)	6	4½	3½ - 6½
1½ (37.5)	5½	4½	3 – 6
2 (50.0)	5	4	2½ - 5½
3 (75.0)	4½	3½	1½ - 4½

Note: ACI 201.2R, 211.1, and 345 recommend and ACI 318 and ASTM C 94 specify a tolerance of 1½ % on total air content. ACI 301 states a range and doesn't indicate a further tolerance. ASTM C 94 also describes air content for mild exposures. These are 1½ % less than indicated for moderate exposure and aggregate sizes up to 1 inch, and 2% less for larger aggregates. The requirements of ACI 318 and ASTM C 94 match the recommended total air content values of ACI 201.2R, ACI 211.1, and ACI 345. The required or recommended air contents depend on aggregate size and freeze-thaw exposure conditions. In severe exposure cyclic freezing, concrete saturation and deicing salt are expected; in moderate exposure cyclic freezing is expected but continuous saturation of concrete or salt are not expected; in mild exposure freezing is not expected, air is recommended not for durability but for improved workability and strength in low-cement-factor concrete.

Table 2: Common industry documents recommending *total air contents* needed for durability of concrete containing different nominal maximum size aggregates, and, exposed to various environmental conditions of freezing and thawing. A mere fulfillment of these requirements does not necessarily guarantee scaling resistance, unless the concrete has a good air void system, i.e., a system of numerous fine, discrete, spherical and near-spherical, closely-spaced, and uniformly-distributed *entrained air voids* having a specific surface of at least 600 in²/in³ and a void-spacing factor of less than or equal to 0.008 in.

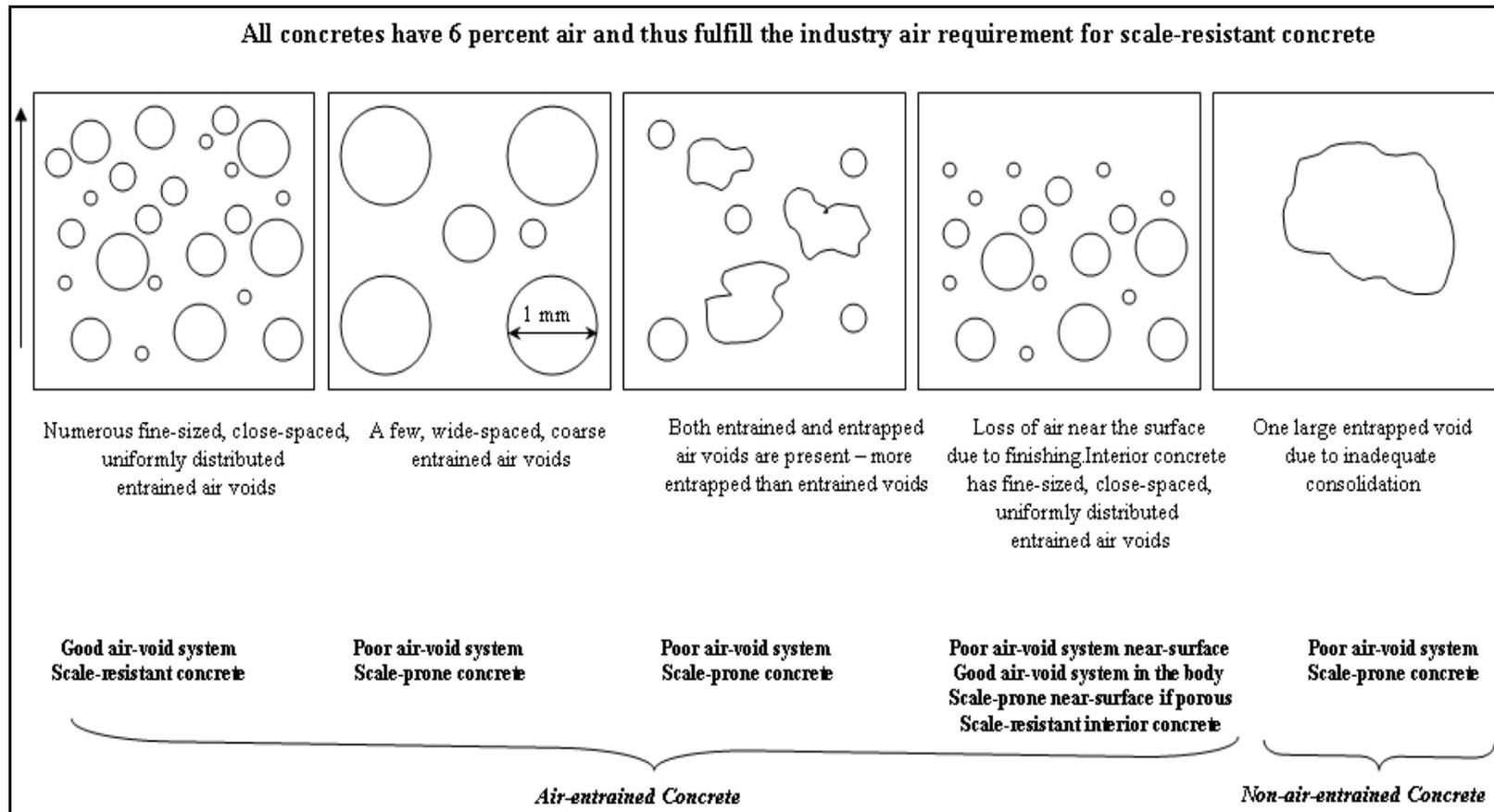


Figure 3: Schematic diagrams depicting cross sections of concrete slabs containing different types of air voids – entrained and entrapped – all at a *total air content* of 6 percent. Despite fulfilling the common industry requirements of total air contents by all these scenarios, only the slab containing uniformly distributed adequate entrained air voids at the surface region (the left most one in the diagram) will be scale-resistant. The others, such as the middle three scenarios, will be susceptible to scaling, and more so in the presence of salts, even with air entrainment and 6 percent total air content.

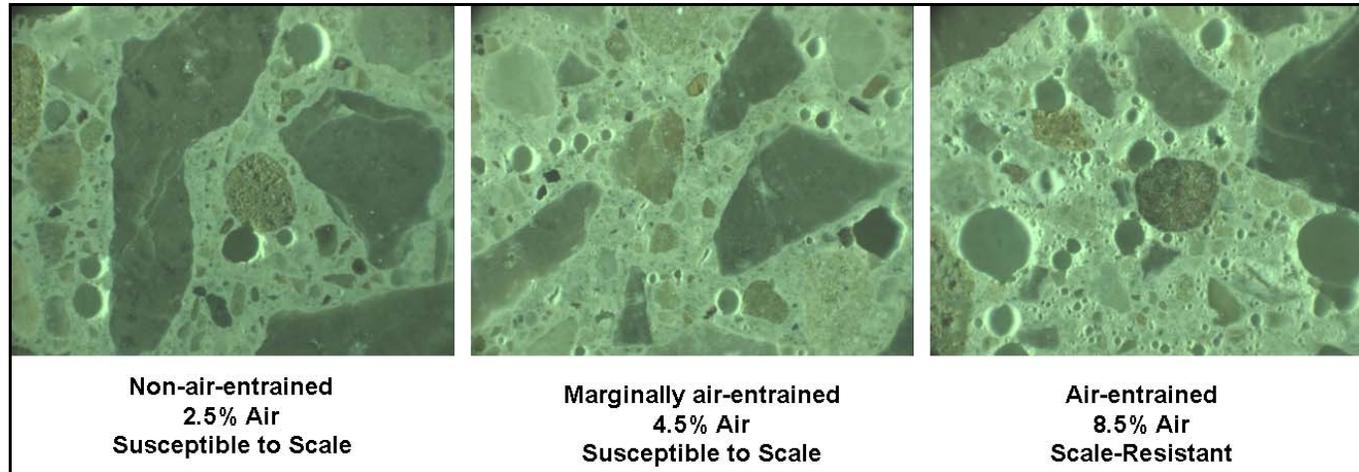


Figure 4a: An example of three different air void systems in concrete – the left and middle concretes are susceptible to scaling, whereas the right one is scale-resistant. The figure shows difference in air void systems between non-air-entrained, marginally air-entrained, and adequately air-entrained concretes. The figure does not imply that high air content is necessary for scaling resistance. Field width of each photo is 7 mm.

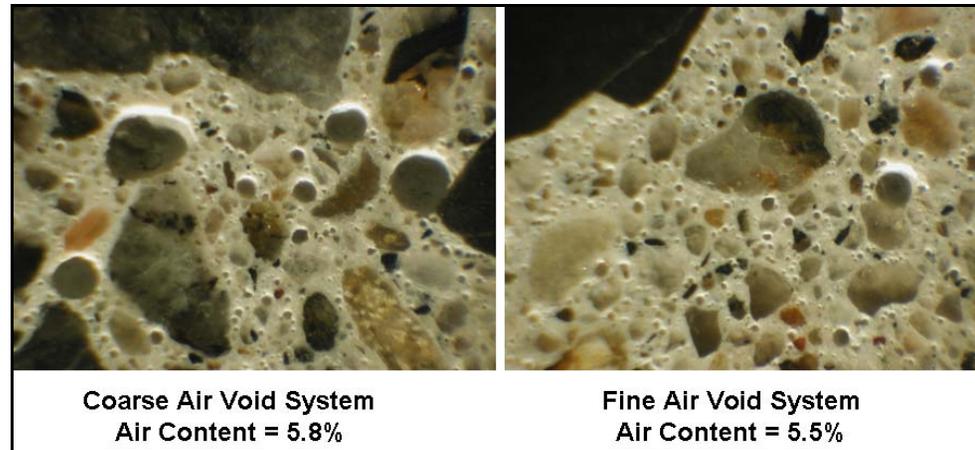


Figure 4b: Another example of two concretes having air entrainment and identical total air contents but the left concrete has a coarser air voids system (i.e., larger air bubbles, lower specific surface, and higher void spacing factor) than the right one. Therefore, despite air entrainment, the left concrete has a lower resistance to distress during cyclic freezing and thawing than the right one. Fulfilling air entrainment and the “total air” requirements do not necessarily guarantee the scaling resistance unless the concrete has an adequate number of air bubbles. Field width of each photo is 7 mm.

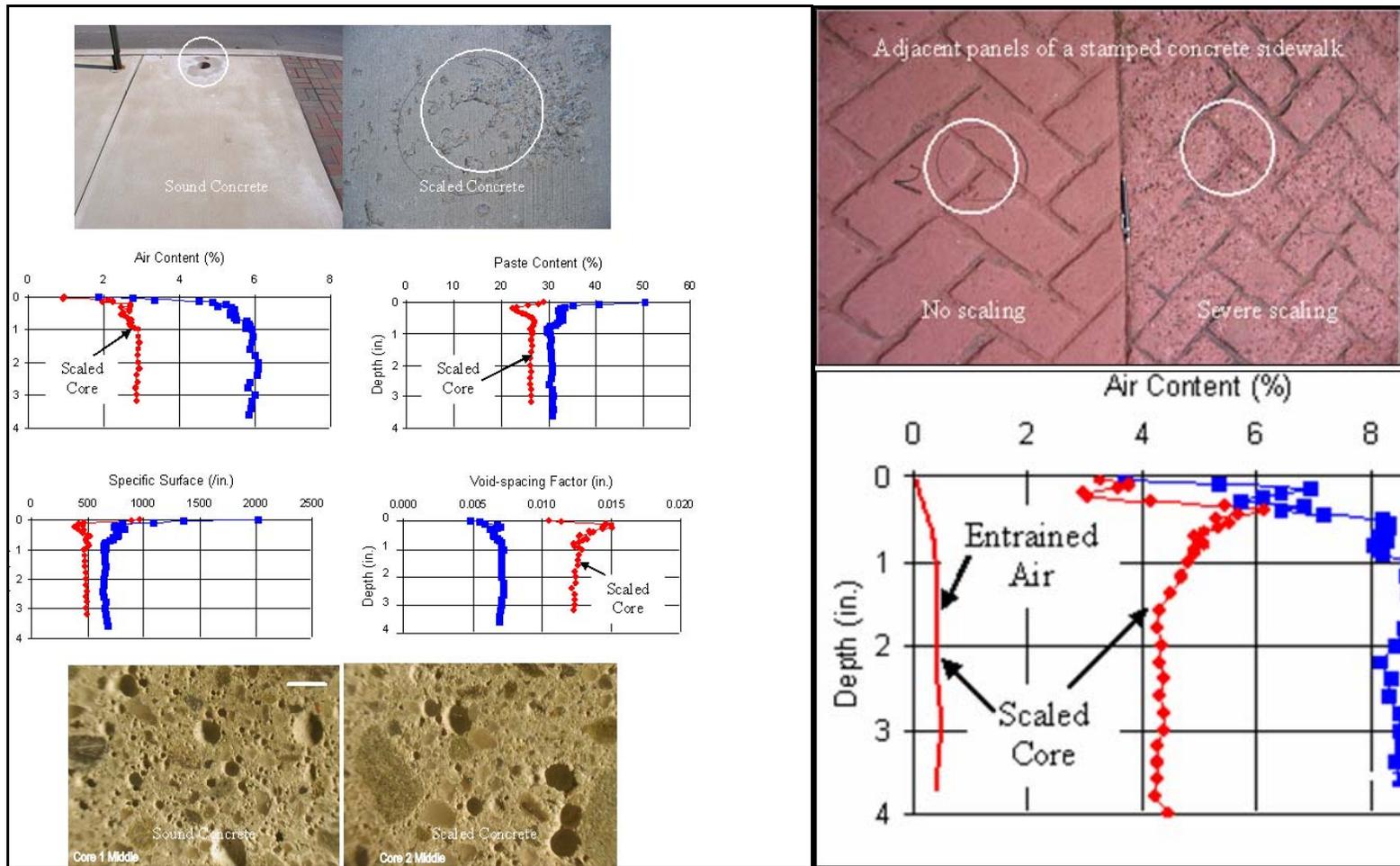


Figure 5: Two case studies (adapted from Jana 2004, [3]; courtesy of the American Concrete Institute) showing scaling of concrete sidewalks due to improper air entrainment. In both cases, adjacent panels of sidewalks show contrasting surface conditions (scaled-versus-sound), which are determined to be due to: (a) coarse air void system in air-entrained concrete in the scaled panel in the left photos, and (b) accidental absence of air entrainment in the scaled panel in the right photo. In all profiles of air void parameters, scaled panel concretes are shown in red and sound panel concretes are shown in blue. These are a few examples of the lack of quality control, and no air void measurements in the fresh concrete during placement, which can lead to scaling.

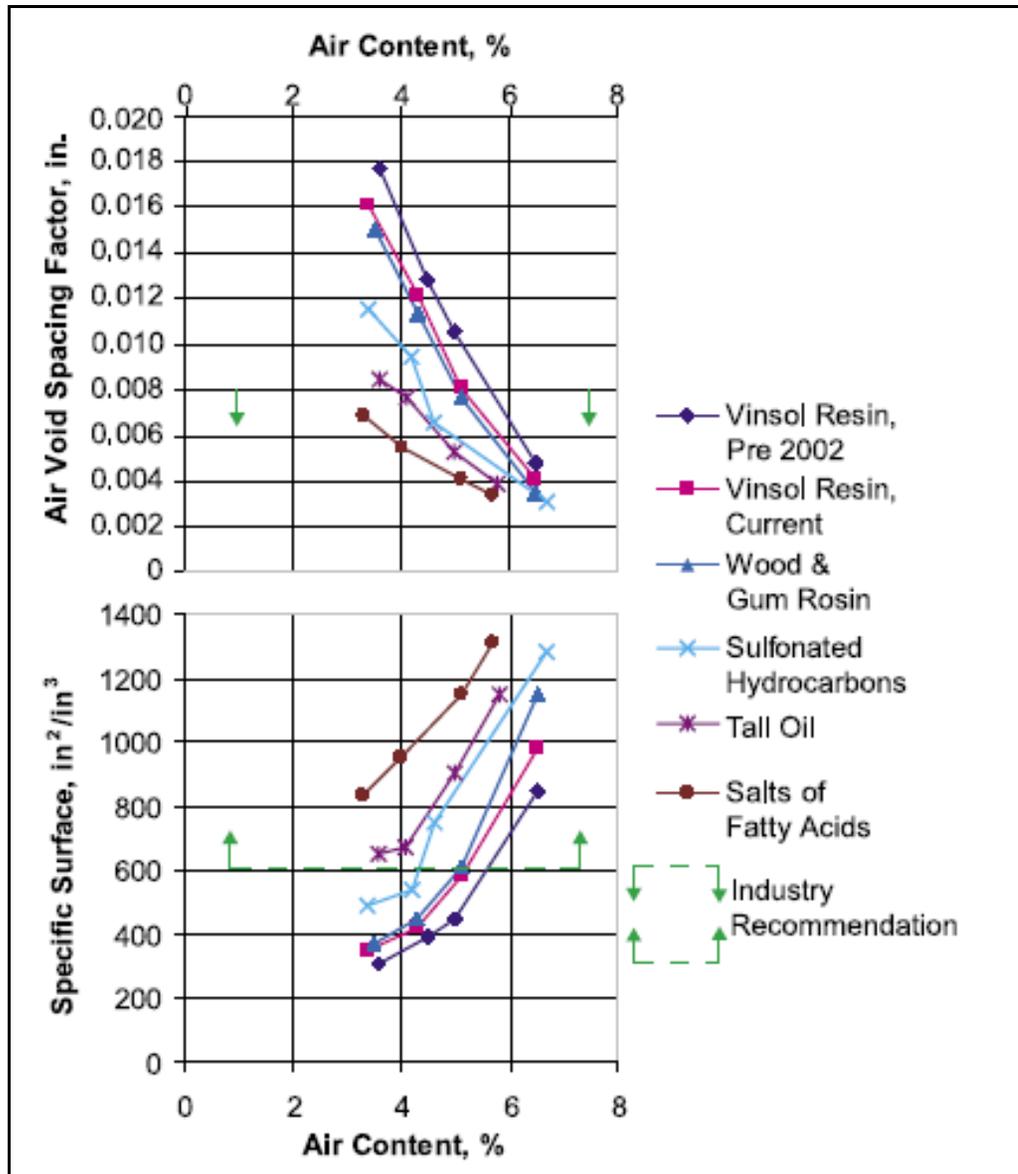
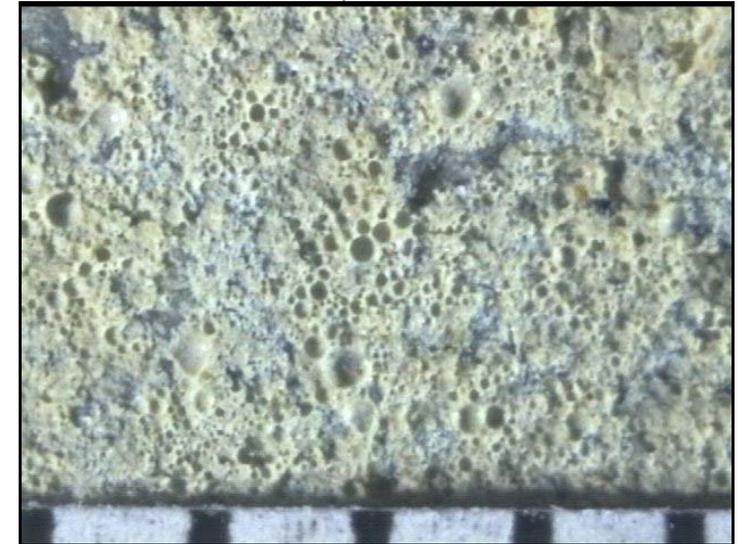


Figure 6: Graphs illustrating effectiveness of new generation of air entraining chemicals in stabilizing good air void systems in concrete (adapted from Jana et al. 2005, [5]; courtesy of the American Concrete Institute). Compared to the conventional vinsol resin-based air entraining agent, at a given air content, new chemicals, such as tall oil or salts of fatty acid can generate significantly finer air bubbles with a higher specific surface and a lower void spacing factor, which is very effective in providing the freeze-thaw resistance of paste. Excessive addition of these new chemicals, however, can generate too many air bubbles, which can affect the compressive strength of concrete. The bottom photo shows frothy textured paste from such excessive addition of an air entraining agent. A controlled addition of these new chemicals, therefore, can stabilize an excellent air void system in concrete at air contents lower than that of common industry recommendations.



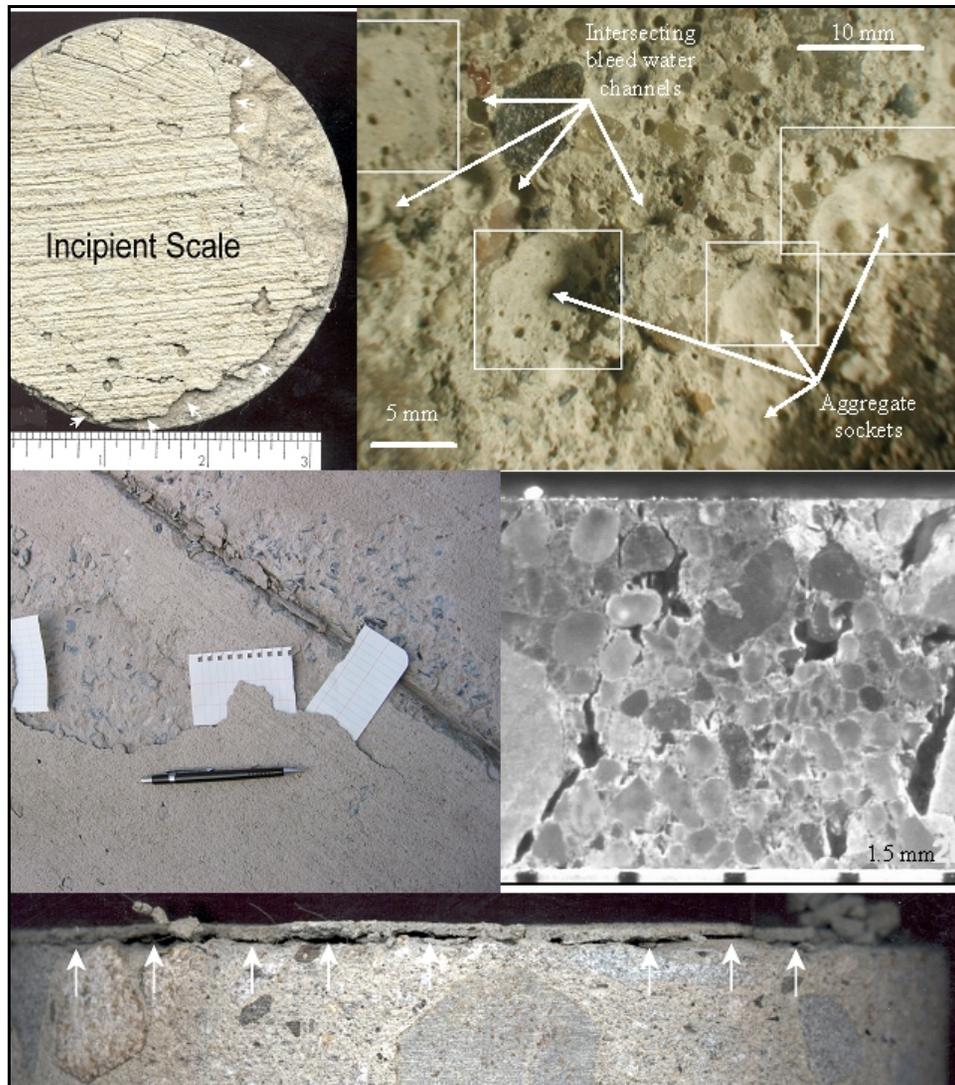


Figure 7: Examples of finishing improprieties that can lead to scaling (some photos are adapted from Jana 2004, [4]; courtesy of the American Concrete Institute):

The top left photo shows a thin sheet of a fine broom-finished surface ($\frac{1}{16}$ -in. thick) loosely adhered to the main body of the concrete with a separation in between.

Top right photo shows the texture of the underside of a “scale” that has been separated from the main body. Notice the coarse aggregate sockets and intersecting bleed water channels indicating entrapment of bleed water beneath the finished surface.

The middle left photo shows thin sheets of incipient scales that are about to scale off from the concrete underneath. Here, scaling is due to premature finishing prior to the cessation of bleeding, which has caused entrapment of bleed water beneath the finished surface.

Middle right photo is a cross section of a concrete slab showing long bleed water channels oriented almost perpendicular to the finished surface at the top, indicating excessive bleeding of the concrete.

The bottom photo shows side view of a core from a concrete sidewalk having scaling and incipient scaling. Here, the finished surface is loosely adhered to the main body with a discontinuous separation between the finished surface and the body.

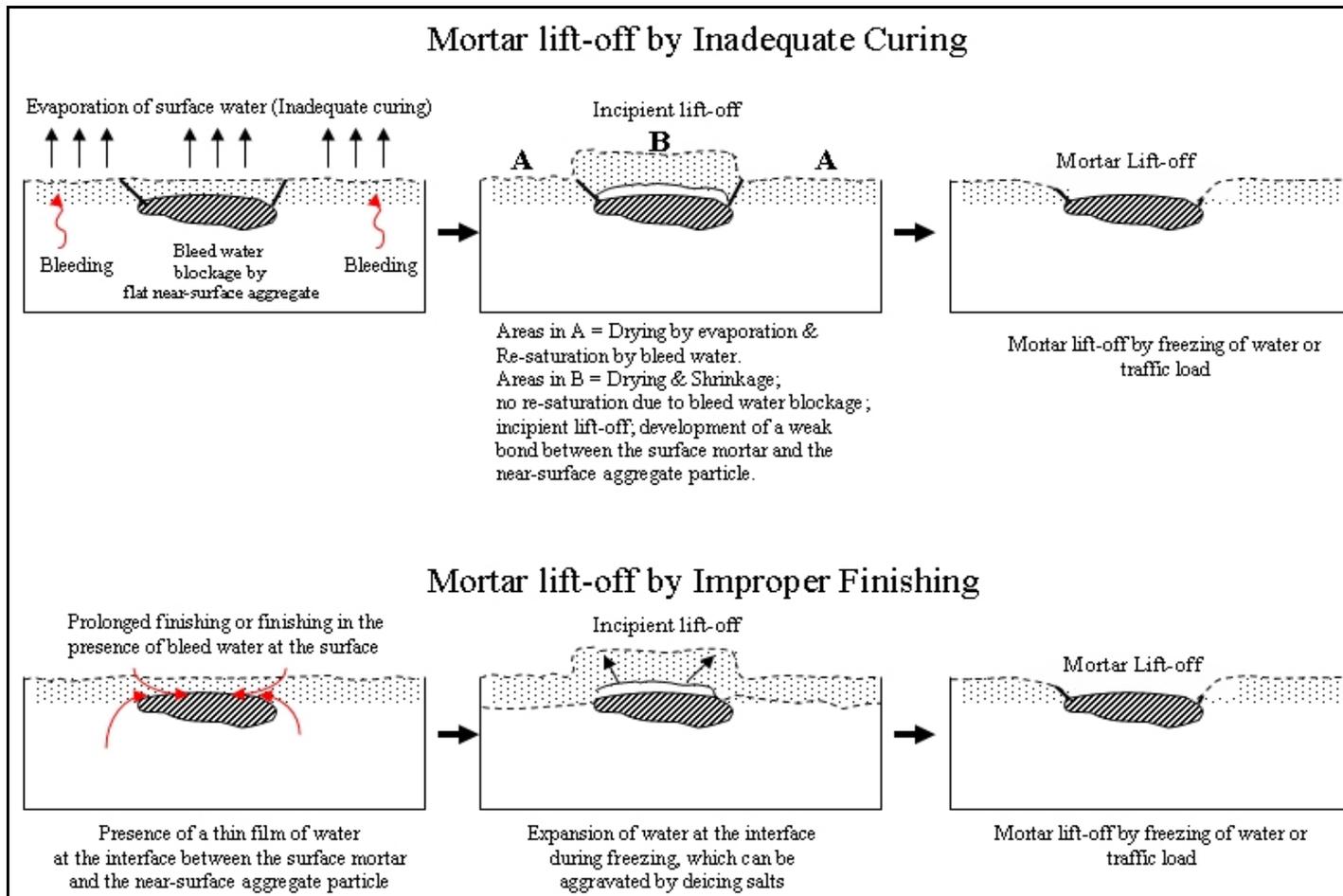


Figure 8: Schematic diagrams showing mechanisms of mortar lift-offs by inadequate curing (top) and improper finishing operations (bottom). Inadequate curing of a finished surface during exposures to hot, windy, sunny, or dry weather conditions can lead to rapid evaporation of the surface water, and subsequent shrinkage of the finished surface. A thin sheet of the finished mortar, situated above the flat top side of a near-surface aggregate particle develops shrinkage cracks, and eventually lifts off from the body, exposing the underlying aggregate particle. In the bottom photo, prolonged finishing, or finishing in the presence of bleed water at the surface develops a weak zone between the finished surface and underlying flat topside of an aggregate particle, which can eventually lead to lifting of the surface, and exposure of the aggregate particle.

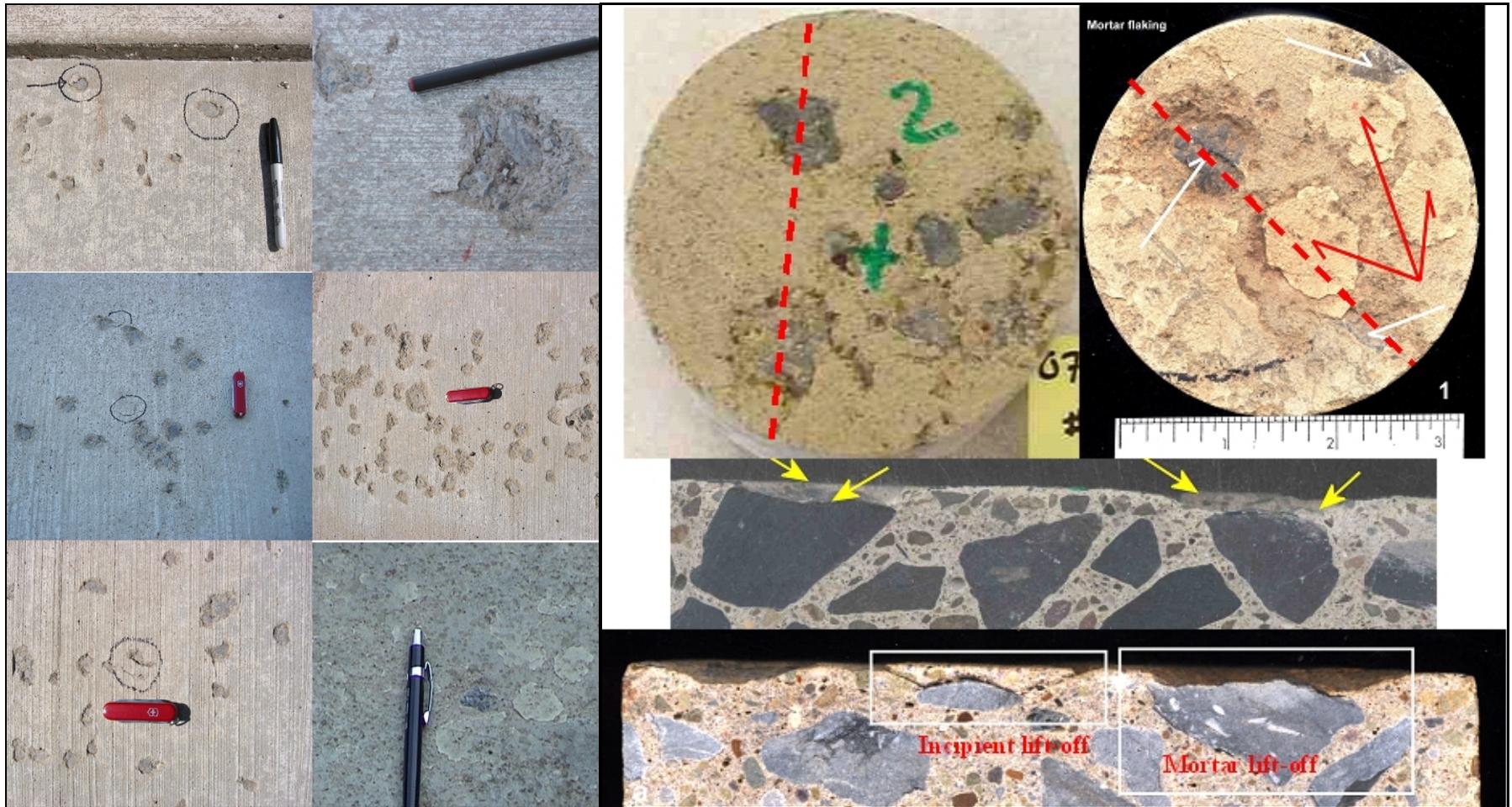


Figure 9: Various examples of mortar lift-offs. The left photo shows various examples of mortar lift-offs where isolated areas on concrete surface show losses of finished surface mortars and exposures of near-surface aggregate particles. The right photo shows some core samples taken from over mortar lift-offs (top right photos), and their vertical cross sections at the top portions (bottom right photos), where the finished surface is either lost, or loosely adhered to the near-surface aggregate particle. The aggregate itself is dense crushed limestone, which did not contribute to the distress.

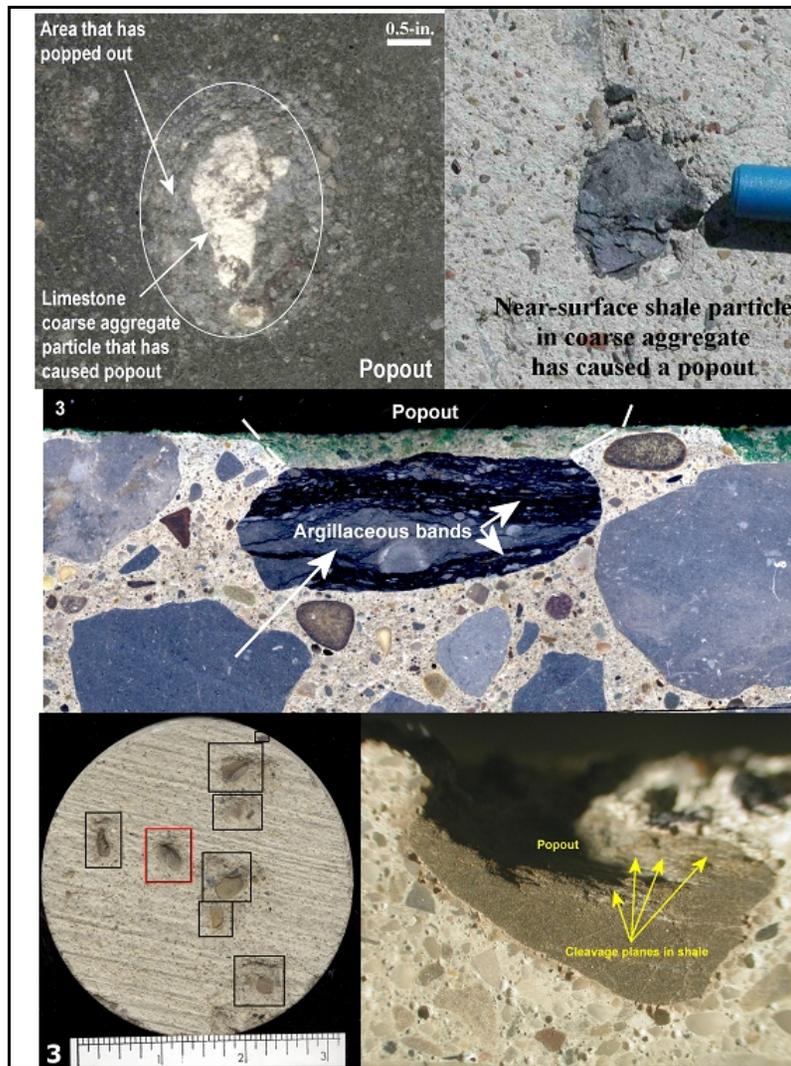


Figure 10: Various examples of aggregate popouts due to freezing of near-surface, unsound aggregate particles at critically water-saturated conditions.

The top left photo shows intense fracturing and popout of a near-surface porous limestone coarse aggregate particle that has caused development of a conical depression on the finished surface.

The top right photo shows fracturing and popout of a black shale coarse aggregate particle on a concrete sidewalk surface that has been exposed to cyclic freezing and thawing. The aggregate particle shows typical sheet-like fracturing along the rock cleavage planes, due to freezing and expansion of water absorbed by the particle.

The middle row photo shows vertical cross section of a concrete slab where thick dark argillaceous bands in a near-surface crushed limestone coarse aggregate have caused unsoundness (expansion) and popout.

The bottom row, left photo shows various isolated occurrences of aggregate popouts on a broom-finished concrete driveway causing shallow conical depressions and exposures of fractured remains of the aggregate particles at the base of the popouts.

The bottom right photo shows one such aggregate particle from left photo where the aggregate shows clear fracturing and loss of a portion of it, along with the finished surface.

Table 3: Some petrographic observations of concrete scaling and associated surface distress due to various factors (a combination of many of these factors is also common and found in many case studies by the author):

1. Scaling due to Poor Air-void System in Concrete

Scaling due to Poor Air-void System	Petrographic Observations
[1] Scaling due to cyclic freezing and thawing of a non-air-entrained concrete (or in the presence of salts)	(1) Concrete does not have 'entrained' air, which is the intentionally introduced fine, discrete, spherical or near-spherical air voids having sizes of 1 mm or less needed for the protection of paste against freezing. It is not uncommon for a non-air-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. (2) The “scales” (i.e., thin sheets of surface) often have lenticular configurations with tapered edges. (3) Scaling often occurs by surface-parallel cracks that transect and circumscribe the aggregate particles and extend to the depth of freezing.
[2] Scaling due to cyclic freezing and thawing of an inadequately air entrained concrete (or in the presence of salts)	(1) Concrete does have 'entrained' air, but the total air content is less than the amount necessary for freeze-thaw resistance of paste. (2) Despite having an industry-recommended “total air content” (e.g., 6 percent air for a concrete containing 1-in. size aggregate), the majority of the voids are of “entrapped air” (formed probably due to inadequate consolidation of concrete), the amount of “entrained” air content (which is essential for the overall protection of paste) is low and inadequate to provide the necessary protection of paste. (3) Concrete has adequate entrained air in the body but the surface region has inadequate air due to the loss of some air during the finishing operations.
[3] Scaling due to cyclic freezing and thawing of an improperly air-entrained concrete (or in the presence of salts)	(1) Concrete does have entrained air, and the total air content may fulfill the industry requirements; but the entrained air voids are coarse and wide-spaced – i.e., the specific surface ($< 600 \text{ in}^{-1}$ or $< 23.6 \text{ mm}^{-1}$) and void spacing factor ($> 0.008 \text{ in.}$ or $> 0.2 \text{ mm}$) of air-entrained concrete are outside the industry recommendations.

2. Scaling due to Improper Finishing, Curing, or Placement

Scaling due to Improper Finishing	Petrographic Observations
[1] Scaling due to cyclic freezing and thawing of a concrete that has been finished prematurely prior to the cessation of bleeding; or a prematurely finished indoor concrete slab not exposed to freezing but to regular traffic loads	(1) A distinct, narrow separation (not a crack) between the loosely adhered finished surface (the incipient scale) and the body of the concrete; (2) More or less uniform thickness of loose scales; (3) Texture of the underside of the incipient scale shows irregularly shaped water voids that are indicative of bleed water entrapment; (4) Narrow, vertical, stringy voids or bleed water channels in the body, some of which may be intersected by the scaled surface; (5) Evidence of excessive bleeding in the concrete such as progressively increasing w/cm toward the top and laitance; (6) The textures of the freshly scaled surface and the underside of the loosely adhered, incipient scale show soft, high w/cm paste relative to the w/cm in the body; (7) The scaled surface (and the underside of incipient scale) contains abundant coarse aggregate sockets that are indicative of a weak aggregate-paste bond due to the presence of excess water during finishing.
[2] Scaling (dusting, abrasion) due to finishing in the presence of excess water at the surface – either water added during finishing, or finishing in the presence of bleed water at the surface	(1) Soft, porous, fragile, absorptive, often dusty-natured, high w/cm , light gray to cream colored paste on the exposed, scaled, or finished surface and in the near-surface region (i.e., within the top 10 to 20 mm); (2) Distinct variations of these above-mentioned surface paste properties from the paste in the interior of the slab; (3) High depth of carbonation; (4) The abundance of residual portland cement particles is significantly less at the surface than in the interior; the degree of hydration of cement particles is adequate at the surface.

[3] Scaling (and delamination) due to prolonged finishing and lack of air voids at the surface of an air-entrained concrete	(1) Severe loss of air at the surface and in the near-surface region of an air-entrained concrete (usually to a depth of 1 in.) resulting in a dense, hard, dark gray, low (or no) air near-surface zone rich in the mortar fraction of the concrete; (2) Distorted air voids (tears, oval-shaped voids) immediately beneath the finished or scaled surface.
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3. Scaling due to Exposure to Salts

Salt Scaling of a properly air-entrained and well-constructed concrete	Petrographic Observations
[1] Scaling due to early exposure to salt prior to the attainment of maturity	(1) Evidence of high chloride at the surface compare to that in the body of a well-cured, well-placed, adequately air-entrained concrete containing sound aggregates; (2) Background information suggested placement of concrete during or immediately prior to the exposure to freezing (late fall or winter placement); (3) Evidence of freezing of the surface region of a well-cured, well-placed, adequately air-entrained concrete containing sound aggregates – ether at plastic or semi-plastic state (e.g., ice crystal impressions on paste) or at hardened state (e.g., microcracks); (4) Compressive strength of the outdoor concrete placed during or immediately prior to the freezing season is determined to be less than 4000 psi.
[2] Scaling due to exposure to corrosive salts (e.g., magnesium or ammonium chloride or sulfate)	(1) Softening, dusting, corrosion of finished surface of concrete (sometimes starts as patchy corrosion at isolated locations, especially in areas more exposed to salts than the others); (2) Evidence of high chloride at the surface region, which is detected (usually by SEM-EDS) to be of magnesium or ammonium salts; (2) Corrosion of paste at the surface due to decomposition of cement hydration products in the presence of salts; (3) Evidence of surface parallel cracks, sometimes containing salt crystals in the decomposed paste; (4) Evidence of alteration of paste and the presence of alteration products in the surface region (e.g., magnesium hydroxide by reaction of magnesium chloride salts with the calcium hydroxide component of cement hydration).
[3] Scaling due to reversible phase transformation of soluble sulfate and/or carbonate salts of calcium, magnesium, or sodium due to cyclic wetting and drying (see Section 5 for such reactions).	(1) Scaling of concrete surface as thin sheets, corrosion, and spalling often occurs in locations where concrete is exposed to such salts in the environment and undergoes daily fluctuations in temperature and relative humidity, common in areas (e.g., ground levels) exposed to wetting and drying; (2) Diagnosis of salts in the concrete, especially at the surface region (by microscopy, chemical analysis, or XRD); (3) No clear evidence of chemical alteration or decomposition of cement hydration products in paste such as the ones occur in the presence of “corrosive salts” but physical deterioration of concrete by reversible phase transformations of salts due to cyclic wetting and drying; it is the expansion associated with the increase in the solid volume of the hydrous phases of salts by wetting of anhydrous or less hydrous salts (e.g., transformation of thenardite, Na_2SO_4 to mirabilite $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), which causes the scaling.

4. Aggregate popout, D-Cracking, and Mortar Lift-off

Aggregate Popout, D-Cracking, and Mortar Lift-off	Petrographic Observations
[1] Aggregate Popout	(1) Evidence of expansion and fracturing of the exposed aggregate particles at the locations of popouts; (2) Detection and identification of “unsound” aggregate particles in the aggregate remains at the base of the popouts, which are either susceptible to distress due to freezing at water-saturated conditions (e.g., argillaceous rocks, siltstone, porous sandstone, limestone), or are alkali-silica reactive and have caused expansion due to such a reaction in the presence of moisture (e.g., silicic volcanic rocks, chert, chalcedony, rocks having strained quartz), or aggregate particles have deleterious coatings or impurities to render them unsound in a cyclic freezing environment.
[2] D-Cracking	(1) Detection of unsound aggregate particles that are susceptible to cause expansion during freezing at critically water-saturated conditions (e.g., porous carbonate rocks); (2) Locations of such distress mostly along the base of the joints in pavements where steady supply of moisture is available for these unsound aggregate particles to remain saturated during freezing.
[3] Mortar Lift-off	(1)The exposed aggregate particles at the locations of mortar lift-offs are determined to be sound, frost-resistant and not responsible for the distress; (2) Evidence of the presence of flat topsides of near-surface coarse or fine aggregate particles immediately beneath the finished surface, and at the locations of the mortar lift-offs; (3) Evidence of rapid evaporation of surface water, restricted hydration of cement particles at the surface mortar, bleed water blockage by the flat topside of aggregate beneath the lift-offs, and weak bond or “gap” between the thin sheets of finished surface mortar and the underlying flat top surface of the near-surface aggregate at the locations of “incipient lift-offs” (i.e., where the thin sheet of mortar, through lifted off from the aggregate is still loosely adhered to the concrete).

5. Reversible Phase Transformation of Various Soluble Salts that can cause Scaling by Salt Hydration Distress

Hydration Reactions	Molar Volumes (cm ³ /mol)		Decrease in Reaction Volume (%)	Increase in Solid Volume to Cause Salt Hydration Distress (%)
	Solid Reactant	Solid Product		
CaSO ₄ + 2H ₂ O = CaSO ₄ .2H ₂ O (Anhydrite) (Gypsum)	45.99	74.21	- 9.5	+ 61.3
Na ₂ SO ₄ + 10H ₂ O = Na ₂ SO ₄ .10H ₂ O (Thenardite) (Mirabilite)	53	220	- 5.6	+ 315.1
Na ₂ CO ₃ .H ₂ O + 9H ₂ O = Na ₂ CO ₃ .10H ₂ O (Thermonatrite) (Natron)	55.11	198.7	- 8.5	+ 260.5
Na ₂ CO ₃ .H ₂ O + 6H ₂ O = Na ₂ CO ₃ .7H ₂ O (Thermonatrite) (7-hydrate)	55.11	153.7	- 5.8	+ 178.9
MgSO ₄ .H ₂ O + 6H ₂ O = MgSO ₄ .7H ₂ O (Kieserite) (Epsomite)	56.7	146.71	- 10.9	+ 158.7