

SWIMMING POOL PLASTER DETERIORATION – OVERVIEW & CASE STUDIES

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ABSTRACT

Deterioration of swimming pool's cementitious coating (plaster) is a complex process involving interactions of four closely related systems – (a) the pool water containing water-treatment and other chemicals, (b) the plaster, (c) the shotcrete or concrete substrate on which the plaster is applied, and, (d) the environments in which the plaster was placed and is in service. Common forms of pool plaster deterioration include: (a) cracking of pool plaster by various mechanisms, such as shrinkage prior to water immersion, structural movement of pool such as settlement of substrate, or, expansive chemical reactions within the substrate putting the plaster in tension; (b) softening of plaster due to the use of inferior plaster materials or mix, improper placement temperature and practices, and interactions with aggressive pool water; (c) debonding of plaster from substrate, or debonding of one coat of plaster from its undercoat; (d) sporadic mottled or blotchy gray-hued abnormal discoloration of plaster surface; (e) staining discoloration from various sources; (f) dissolution of plaster (leaching) and associated etching by aggressive acid water, (g) scaling or precipitation of secondary deposits on plaster surface by alkaline water chemistry; (h) combined aggressive chemical attacks by alternating acidic and basic pool water chemistries on the plaster surface and associated etching and staining; (i) spot alterations from aggressive water attack and/or improper plastering processes; (j) plaster surface popout and local staining by unsound or reactive sand particles in plaster; and (k) freezing and thawing damage of plaster surface prior to water immersion, or of portions not immersed in water, etc.

Petrographic examinations (optical and scanning electron microscopy) and chemical analyses of plaster samples from damaged pools are often helpful to diagnose the cause(s) of plaster deterioration and its extent. Case studies presented herein are of samples received to our laboratory from various pools at different degrees and types of deterioration. Studies discussed include: (a) cracking of pool plasters by excessive shrinkage of plaster and deleterious alkali-silica reaction of aggregates in the concrete substrate, (b) plaster debonding and blistering, (c) plaster etching and scaling by imbalanced pool water, (d) mottled discoloration of plaster, (e) staining by brick masonry copings, and (f) spot alterations and associated spot staining of plaster.

INTRODUCTION

Swimming pool plaster is a relatively thin [thickness 9.5 to 19 mm ($\frac{3}{8}$ to $\frac{3}{4}$ in.)] layer of dense cementitious coating containing a mixture of white portland cement (or pigmented cement), aggregate (commonly calcium carbonate aggregate such as limestone or marble chips, or siliceous aggregate), and water, with or without other admixtures that when mixed thoroughly, placed properly over the shotcrete or concrete substrate, and finished and cured accordingly, forms a decorative, maintainable, and near water-tight finish. Plaster containing white portland cement and marble chip aggregate has been one of the most commonly applied pool finishes used over the past 40 years. Deterioration of swimming pool plaster, prior to its anticipated service life, has been a growing concern of not only the pool owners but also of plasterers, service and chlorine industries, and other professionals in the pool and spa industry. Concerns commonly raised for plaster deterioration include inferior plaster materials and plaster quality, improper proportioning (e.g., excessive addition of calcium chloride admixture), improper finishing, substrate expansion or settlement, aggressive pool water attacks, etc. Increasing use of various water treatment chemicals multiplies the complexity of interactions of pool water with its cementitious coating and sometimes contributes to the plaster problems. This paper provides an overview and case studies of various pool plaster deterioration.

TYPES OF SWIMMING POOL PLASTER DETERIORATION

The Technical Manual of National Plasterers Council (NPC) provides a good overview of various deterioration of swimming pool plaster [1], which is summarized below. Many of these distress mechanisms are manifestations of one or a combination of the following:

- (a) Interactions between the swimming pool water and the plaster (the imbalance of the pool water chemistry and its deleterious effects on the plaster causing leaching/etching, or staining/scaling type deteriorations);
- (b) Use of improper plaster materials, mix (e.g., improper amounts of sand, cement, or calcium chloride admixture), or construction practices (improper finishing, inadequate curing and rapid drying of freshly placed plaster, placement in subfreezing temperatures, placement on improper substrate surface, etc.) causing plaster softening, debonding, and discoloration;
- (c) Effect of unstable substrate on plaster (expansion, settlement, source for plaster staining, etc.) causing plaster cracking or staining;
- (d) Improper design of pool; and,
- (e) Improper pool maintenance (e.g., excessive dosage of some water-treatment chemicals).

A comprehensive list of pool plaster deterioration includes [1]:

- (a) Plaster **cracking**, either by plaster shrinkage prior to immersion in water, or by structural movement, subgrade settlement, or, soil/substrate expansion putting plaster in tension;
- (b) Plaster **softening**, due to use of improper plaster mix, materials, or proportions, interaction with aggressive pool water, or placement in subfreezing temperatures;
- (c) Plaster **debonding**, either debonding between the coats of plaster, or of plaster from substrate, incipient delamination (e.g., blisters, buckles), and spalls;
- (d) Plaster **discoloration** as sporadic shaded, gray-hued areas of excessive mottling, blotchiness;
- (e) Plaster **staining** at isolated small localized areas having colors distinct from the rest;
- (f) Plaster **etching** by aggressive chemical attack;
- (g) Plaster **scaling**, efflorescence, and salt crystallization by imbalanced alkaline water;
- (h) **Spot alteration** (i.e., spot staining, soft spots, spot leaching, spot etching) as isolated dime-sized whitened or lightened (sometimes stained) spots on smooth plaster surface;
- (i) **Surface pitting**, popout, and stain by unsound or reactive sand aggregate in plaster;
- (j) **Freezing and thawing damage** of plaster, especially prior to immersion in water, or in portions above water; and,
- (k) Aggravated surface mottling of hard-troweled plaster due to **carbonation** prior to immersion in water, or dissolution of carbonated plaster as water-soluble bicarbonate by water having a low carbonate alkalinity.

The common types of plaster deterioration, which the author has frequently encountered, are: plaster cracking, delamination, discoloration, staining, etching, scaling, surface pitting, and spot alteration.

The primary focus of the paper is to demonstrate the role of various laboratory investigative methods in diagnosing the cause(s) and extents of these plaster problems. Fifteen case studies are presented discussing a multitude of plaster problems from cracking to debonding to discoloration/staining to etching/scaling, and their causes. An elaborate discussion of spot alteration of plaster is given.

METHODS OF LABORATORY INVESTIGATION OF PLASTER DETERIORATION

Due to the nature and complexity of various deterioration mechanisms in a swimming pool plaster, appropriate sampling and comprehensive examination of plaster samples in the laboratory are essential. Samples should be collected from areas of plaster surface showing visible deterioration, as well as, sometimes from less damaged or sound areas. Sample thickness should encompass not only the plaster but also portions of concrete or shotcrete substrate. Usually 3 to 4 in. diameter drilled core, or at least 4 to 10 in. size square or rectangular saw-cut samples are collected. Information needed with samples include but are not limited to photographs of plaster surface showing damage and of sample locations, project specification, pool plaster and substrate mix designs, placement environment and weather, specified coating thickness, plaster materials' (cement, sand, admixture) specifications, raw plaster cement and sand for separate examinations (in specific cases of investigation of sources of staining discoloration), etc.

Methods of laboratory investigation of pool plaster deterioration include:

- (a) Petrographic examinations *a la* ASTM C 856 and ASTM C 1324 [2] by using the methods of optical microscopy (reflected and transmitted light observations of as received, fractured, lapped, thin sectioned, or polished samples), scanning electron microscopy (backscatter and secondary electron imaging), and associated energy-dispersive x-ray microanalysis. Optical microscopy is helpful to identify composition, mineralogy, and microstructure of aggregates and cement paste in the plaster and substrate, evidence of deterioration on plaster surface from scaling and etching, and evidence of deterioration in the substrate. Scanning electron microscopy and x-ray microanalysis can investigate plaster deterioration in a great detail and determine compositions of scales, stains, leached paste, depth of deterioration, etc.;
- (b) X-ray diffraction analysis of plaster can detect stain-forming minerals or metals, and any unusual compositions of plaster and substrate;
- (c) Acid-soluble chloride analysis (*a la* ASTM C 1152 [3]) of bulk plaster can estimate dosage of calcium chloride admixture, and any over-dosage or related plaster problems (such estimate, however, must consider chlorides from the pool water and the age of the plaster);
- (d) X-ray fluorescence (XRF), atomic absorption spectroscopy (AAS), or inductively-coupled plasma spectroscopy (ICP) can determine composition of hardened plaster and its ingredients;
- (e) Chemical analysis (pH, alkalinity, calcium hardness, etc.) of pool water containing water-treatment and other chemicals is helpful to determine the balanced versus aggressive chemistry and influence of pool water on plaster properties and performance; and,
- (f) Supplementary physical tests of plaster properties are helpful to access plaster quality, e.g., tests of absorption, specific gravity, volume of permeable voids (*a la* ASTM C 642 [4]), compressive strength (*a la* ASTM C 109 [5]), and water tightness.

Although author's laboratories are well-equipped to perform all these analyses, the methods that the author most commonly use are optical and scanning electron microscopy, and acid-soluble chloride content analysis, which are usually adequate to diagnose reasons for plaster deterioration.

No laboratory method, however, can provide a comprehensive diagnosis without considering all background information related to a project.

Experiments designed with controlled variables of: (a) pool water chemistry (pH, total alkalinity, calcium hardness), (b) dosages of water-treatment chemicals (sanitizers, stabilizers), (c) plaster design (cement factor, water-cement ratio, cement/sand ratio, calcium chloride dosage), (d) finishing techniques (troweled vs. formed surface, over-troweling, re-tempered surface), and (e) other relevant project-specific variables, and their evolution with time are sometimes essential to understand mechanisms of plaster deterioration in the more complex systems of pools in the field.

PLASTER CRACKING

Cracking in swimming pool plaster can be one or a combination of the following types [1]:

- (a) **Closed Shrinkage Cracks** – Development of normal shrinkage cracks (also called check cracks) on a freshly set and hardened plaster surface is not uncommon prior to their immersion in water. They form due to normal moisture loss from plaster as it sets and dries prior to water immersion. These are small hair-like microcracks, usually autogenically sealed by the cement hydration process within days underwater. These cracks are more noticeable during wetting after drying, on smooth hard troweled finishes, and could remain visible if dirt or dust becomes trapped within the cracks prior to sealing by cement hydration products.

- (b) **Open Shrinkage Cracks** – Shrinkage cracks wider than normal check cracks, however, can stay open underwater, and, therefore, require repair. They occur by excessive moisture loss from plaster during drying and setting, and can penetrate from as shallow as $\frac{1}{8}$ in. to the entire thickness of plaster. Open shrinkage cracks can form by: (i) excessive evaporation of water from plaster surface, (ii) water loss from plaster to an absorptive substrate, (iii) water loss from plaster due to placement in hot, windy, dry weather, (iv) excessive addition of water in plaster (over-tempering), (v) use of excessive water during finishing, (vi) finishing with excess water on plaster surface or over-finishing, (vii) excessive water loss while the plaster is in a plastic or semi-plaster state (plastic shrinkage), (viii) use of excess cement, (ix) use of excess calcium chloride admixture in mix¹ (i.e., in excess of the usual limit of 2 percent calcium chloride dihydrate by weight of cementitious materials), (x) delayed filling of pool with water after plastering, and (xi) some combination of all.

- (c) **Structural Movement Cracks** – Structural cracks form due to: (i) substrate or soil expansion and/or settlement, (ii) use of thin plaster coating that cannot withstand stresses related to movement, (iii) improper substrate surface preparation, or, (iv) improper structural design.

- (d) **Tensile Stress Cracks** – Form due to expansion of substrate, such as by alkali-aggregate reactions or other deleterious expansive processes within the substrate (e.g., cyclic freezing, sulfate attack, etc.) putting the outer plaster coat in tension.

Of all the types of pool plaster deterioration that the author has investigated, cracking is, perhaps, the most common, which has caused either minor cosmetic repair or, in worst cases, removal or re-plastering of the plaster. Of all the types of author's plaster cracking projects, the ones related to expansion of substrate by expansive deleterious alkali-silica aggregate reactions, excessive plaster shrinkage at the early age, and substrate settlement are found to be the most common.

Prior to the initiation of a plaster cracking investigation, detailed background information related to the specified plaster composition, components, and mix design, the specified plaster thickness, substrate composition and mix design, plaster placement temperature and weather condition, and other relevant project information are needed. Field photographs showing the type of plaster cracking (e.g., closed polygonal-shaped, random, or longitudinal/transverse, etc.) are essential. Samples should be collected from over the cracks, encompassing the plaster and substrate components.

¹ Addition of calcium chloride within 1 to 2 percent by weight of cement usually increases early strength of plaster by increased rate of cement hydration, especially at cold weather, and thereby may be beneficial (along with increased density, reduced porosity, and increased water tightness). Excessive addition, however, is detrimental as it reduces long-term strength, increases plaster porosity and shrinkage, and imparts darker gray hue on plaster.

Case Study 1 – Plaster Cracking due to Drying Shrinkage of An Excessively Thick Application



Figure 1 – A pool plaster showing random cracks on the steps.

The steps and floor of a swimming pool show extensive closed, polygonal-shaped cracks, many of which are up to 2 mm in surface width, and reported to be “early cracks,” i.e., formed prior to the immersion of plaster underwater.

A 4-in. diameter core sample, taken from cracked plaster showed application of a plaster thicker than the usual industry-practice of $\frac{3}{8}$ to $\frac{3}{4}$ in. thick plaster, measuring up to $1\frac{1}{4}$ in. in maximum thickness, applied in two $\frac{1}{2}$ to $\frac{3}{4}$ in. thick coats, which were intimately bonded to each other; the bottom coat was intimately bonded to a concrete substrate.

The plaster is non-air-entrained (< 2 percent air) and made using fine, angular, marble chip aggregate having a nominal size of 2 mm, and a white portland cement paste having an estimated water-cement ratio of 0.35 to 0.40. Plaster is dense, well consolidated, and free of internal microcracks from any deleterious chemical reactions. Many air voids are lined or filled with fine, fibrous, acicular deposits of secondary ettringite, consistent with the prolonged moisture-saturated condition of the plaster. The plaster does not contain any unsound or reactive aggregate. Surface region of the plaster surface shows carbonation to a depth of 3 to 4 mm.

Acid-soluble chloride content of the plaster, determined in accordance with ASTM C 1152, was 0.71 percent chloride, by mass of the bulk plaster, which corresponds to 3.69 percent calcium chloride addition, by mass of cement², in excess of the recommended maximum limit of 2 percent calcium chloride (assuming minimal contribution of chlorides from the pool water due to young age of plaster).

² Converting percent chloride in hardened plaster (Cl, as determined from ASTM C 1152) to percent calcium chloride admixture addition by mass of cement – If the acid-soluble chloride content of plaster is ‘A’ percent, by mass of plaster (as determined from ASTM C 1152), then it is equivalent to ‘A/O.B.’ percent chloride, by mass of cement (assuming that the plaster contains ‘B’ percent cement, which is usually around 40 percent by mass of plaster but can be determined from ASTM C 114) = This is equivalent to 1.56 (A/O.B) percent anhydrous CaCl₂, by mass of cement, or, 2.08 (A/O.B) percent flake CaCl₂ [i.e., dihydrate, CaCl₂·2H₂O] addition. Usually, 2% flake CaCl₂ is equivalent to 1.5% anhydrous CaCl₂. Usual amount of calcium chloride (i.e., dihydrate) addition is between 1 and 2 percent, by mass of cement. The cement content of a hardened plaster can be determined from ASTM C 114 or ASTM C 1084 by determining silica contents (as % SiO₂) of plaster (e.g., by XRF, AAS or wet chemistry), and cement (or, by assuming 21.0 percent silica as SiO₂ in white portland cement). The determined chloride

The substrate was a 6¹/₂ in. thick, dense, well-consolidated, crack-free, non-air-entrained concrete made using well-graded, well-distributed, sound, crushed, dark, argillaceous limestone and dolomite coarse aggregate having a nominal maximum size of ³/₈ in., well-graded, sound, natural siliceous sand fine aggregate having a nominal maximum size of ¹/₄ in., a portland cement content estimated to be 7¹/₂ to 8 bags per cubic yard, a water-cement ratio estimated to be 0.44 to 0.48, and an air content estimated to be 2 to 3 percent. There is no evidence of alkali-aggregate reaction of either coarse or fine aggregate in the concrete. Lining the walls of many irregularly-shaped air voids in concrete are profuse fibrous secondary ettringite deposits, indicating prolonged moist condition of concrete.

There is no evidence of any deleterious chemical or physical reactions, either in the plaster or in the concrete substrate. Despite the non-air-entrained nature of plaster or substrate and occurrence of pool in an environment of cyclic freezing and thawing, there was no evidence of freezing-related distress in plaster or substrate.

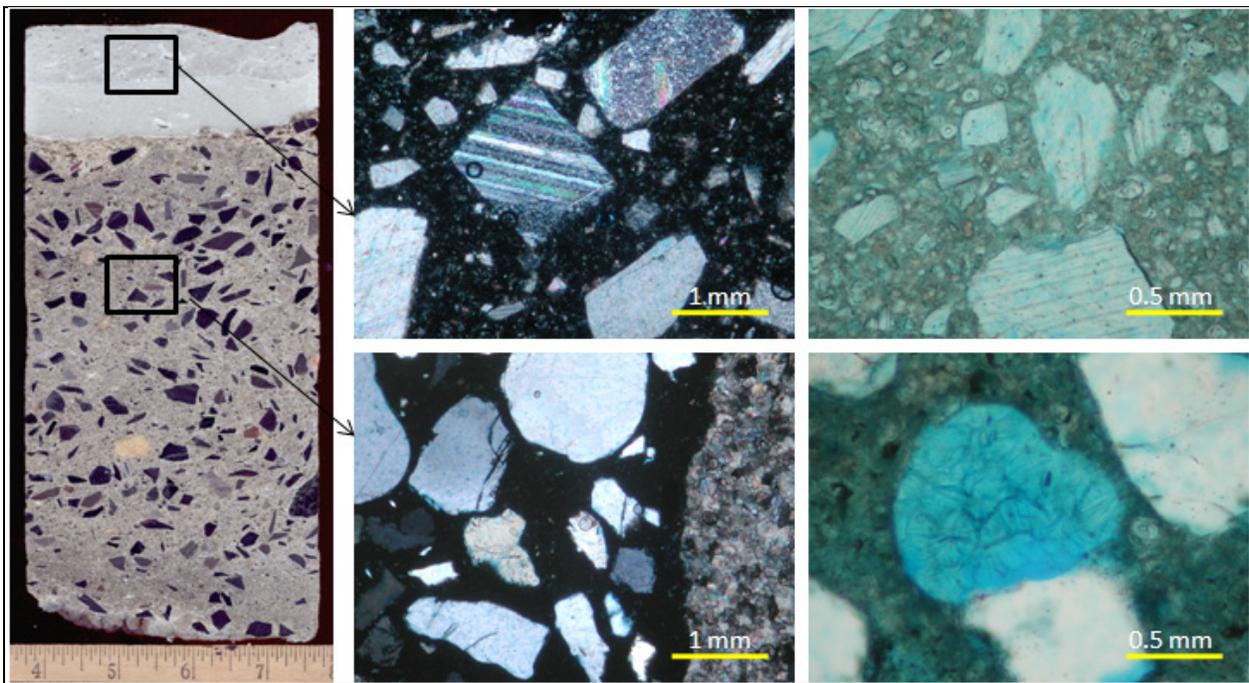


Figure 2 – Left - Lapped cross section of a core from the pool shown in Figure 1. The section shows a thick plaster (comprising two ¹/₂ to ³/₄ in. thick applications), which is intimately bonded to the concrete substrate. Middle = Thin section photomicrographs of plaster (top) and concrete substrate (bottom) showing marble aggregates in plaster and dolomite-quartz aggregates in concrete, and portland cement pastes. Right = Thin section photomicrographs of plaster showing marble aggregates in plaster (top), and an air void in concrete, which is filled with secondary ettringite deposits (bottom).

Based on the reported early occurrence of cracking, the observed absence of any deleterious reaction in the plaster or substrate, the intimate bond of plaster to substrate, and, most importantly, thicker-than-usual application of plaster (in two ¹/₂ to ³/₄ in. coats), and excessive calcium chloride set-accelerating admixture addition (which is known to increase plaster shrinkage), the cracking was judged to have formed due to excessive early shrinkage of a thick plaster prior to immersion in water (steps commonly having thicker plaster than floor and filled at the end usually show more cracking).

content of a field plaster contains not only chloride added in the original plaster mix but also chloride from the pool water - the latter can be higher than the former for an old plaster that has gone through prolonged interaction with pool water. ASTM C 1152 results, therefore, must be used with caution with a prior knowledge of the plaster age.

Case Study 2 – Cracking due to Drying Shrinkage of a Plaster having an Excessive Dosage of Calcium Chloride Admixture



Figure 3 – A pool plaster surface showing closed polygonal-shaped check cracks.

The above photo shows a pool plaster having numerous fine, closed polygonal-shaped cracks. The plaster was approximately $\frac{1}{2}$ in. in thickness and was applied on a concrete substrate. No evidence of any deleterious reaction was found in the plaster, or in the substrate. The plaster contained an excessive dosage of calcium chloride admixture, which is known to cause excessive shrinkage, and, as a result, development of these fine check cracks prior to the immersion of the plaster underwater. The cracks inside the body of the plaster have been partially sealed by cement hydration processes underwater, but were still open enough to be seen on the surface after being in service.

Case Study 3 – Plaster Cracking due to Alkali-Silica Reaction in the Concrete Substrate

Of all the case studies of author related to plaster cracking, alkali-silica aggregate reaction of concrete or shotcrete substrate is found to be the most common, which had placed the plaster in tension, and, as a result, caused plaster cracking. Presented herein is a representative one, where a $\frac{5}{16}$ -in. thick white plaster, intimately bonded to a concrete substrate showed extensive closed, polygonal-shaped cracks, similar in pattern to the one shown in the previous study (Case Study 1).

The concrete substrate, on which the plaster was applied, is non-air-entrained, contained $\frac{3}{8}$ in. nominal maximum sized alkali-silica reactive crushed argillaceous siltstone coarse aggregate, $\frac{1}{4}$ in. nominal maximum sized natural siliceous sand fine aggregate many of which contain severely strained potentially reactive quartz particles, a portland cement content estimated to be 7 to $7\frac{1}{2}$ bags per cubic yard, a water-cement ratio estimated to be 0.44 to 0.48, and an air content estimated to be 3 to 4 percent.

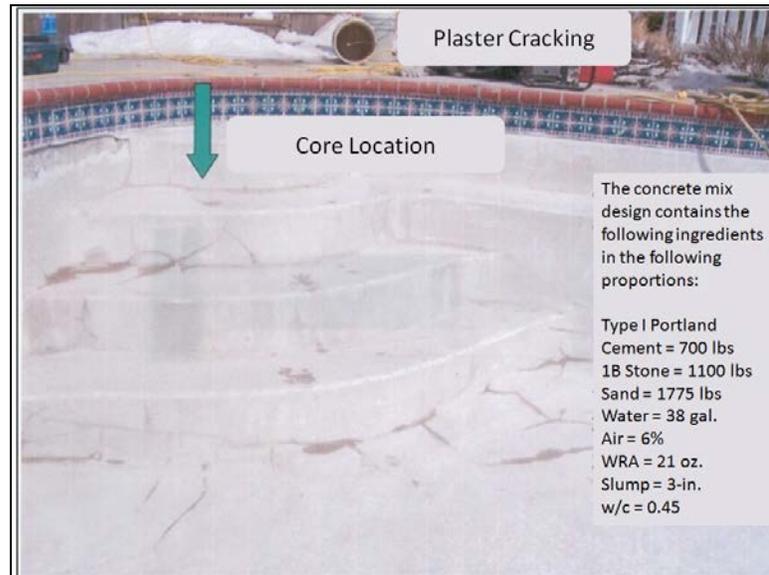


Figure 4 – Steps of a swimming pool showing cracks in plaster, mainly along the bases of the steps. Notice the radial pattern of cracks from the steps. Also shown is the location of the core presented for laboratory study (Case Study 3).

Concrete alkali-silica reaction (ASR) is evidenced by (see Figure 5):

- (a) Dark reaction rims around many reactive coarse aggregate particles; and, soft, white alkali-silica gel deposits on the fractured surfaces within the dark rims of such aggregates;
- (b) Microcracking extending from reactive coarse aggregate into paste; and,
- (c) Various forms of alkali-silica reaction gels in microcracks, entrapped voids, paste, and rims of reactive aggregates that are white porcelain-type, clear glassy and shiny type, light cream colored porcelain-type, layered birefringent-type, and massive isotropic type.

All forms of gel contained sodium, potassium, calcium, and silica (see Figure 5), where calcium in gel came from paste by cation-exchange with alkali; white gel deposits on the fresh fractured surfaces of dark-rimmed coarse aggregate particles, however, do not show calcium enrichment due to the absence of such cation exchange. Associated with ASR gel in many places are secondary ettringite deposits indicating prolonged presence of moisture in the concrete, a condition necessary for sustaining ASR.

Pool plaster was found dense (water-cement ratio estimated to be less than 0.40), made using good quality and well-proportioned, crushed marble chip aggregate and white portland cement. Plaster itself did not show ASR³ or any other deterioration, and simply responded to the substrate expansion by cracking.

³ Pool plaster rarely shows alkali-silica reaction due to the near neutral environment of the pool water. Interior of the plaster, away from the near-neutral surface region, however, can develop ASR if reactive aggregates and high alkali-cements are used in the plaster mixes, which are seldom the case.

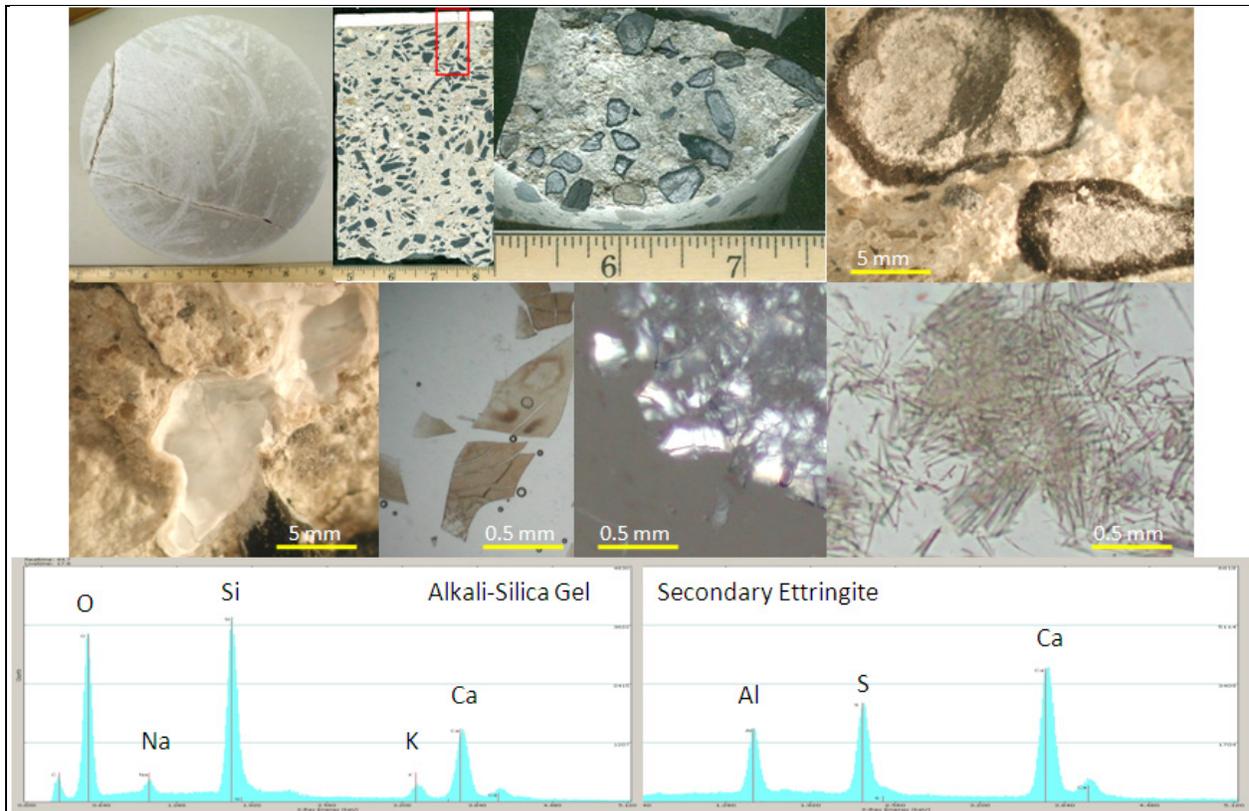


Figure 5 – Top Row from Left = Top surface of a core showing plaster cracks; lapped cross section of the core showing the plaster intimately bonded to the concrete substrate, within the boxed area is a vertical crack that has extended through the entire plaster and a portion of the concrete substrate; fresh fractured surface of core showing white deposits of alkali-silica gel on the fractured aggregate surfaces in concrete that are surrounded by dark reaction rims; photomicrograph of fractured aggregate surfaces showing dark reaction rims and white powdery alkali-silica gel deposits on aggregate surface within the rims. Middle Row = Air voids in concrete lined with white alkali-silica gel; oil immersion mounts of white deposits in voids showing layered and birefringent gel deposits; the right photo shows immersion mount of acicular secondary ettringite deposits that are associated with ASR gel in many voids. Bottom Row = X-ray microanalyses of gel and secondary ettringite deposits in voids.

Case Study 4 – Plaster Cracking due to Combined Cyclic Freezing and Alkali-Silica Reaction in the Concrete Substrate

The steps, wall, and floor of a pool plaster showed extensive closed polygonal-shaped cracking, as well as some long cracks. A core from over a plaster crack was received. The plaster was made using white portland cement and marble chip aggregate. The nominal thickness of plaster, as measured in the core, is 10 to 15 mm. The plaster is intimately bonded to a concrete substrate.

In this case, the concrete substrate, prior to plastering, has undergone deterioration by cyclic freezing and thawing at critically saturated conditions, and, alkali-aggregate reaction. The concrete substrate is dense, non-air-entrained, reasonably consolidated, and made using well-graded, well-distributed siliceous alkali-silica reactive pea-gravel coarse aggregate, natural siliceous sand fine aggregate ($1/4$ -in. size) containing many potentially reactive particles as well, a portland cement content estimated to be from 6 to $6\frac{1}{2}$ bags per cubic yard, a water-cement ratio variable within the sample, and estimated to be from as low as 0.40 in dark patches to 0.48 in lighter gray areas (due to inadequate mixing of batch or tempered water), and air content estimated to be from 1 to 2 percent.



Figure 6 – Photo showing severe polygonal-shaped cracking in a pool plaster.

Concrete and associated plaster cracking are determined to be due to alkali-silica reaction (ASR) in concrete, which is diagnosed by (see Figure 7):

- (a) Extensive microcracking in reactive chert and strained quartzite gravels in coarse aggregate that radiate out to the paste;
- (b) Light to dark brown reaction rims along the periphery of many of these particles; and,
- (c) Extensive development and migration of alkali-silica reaction gels forming within cracks, voids, paste, and margins of reactive particles.

Reactive particles, along with the use of a high-alkali cement and the moist environment in the concrete have triggered the deleterious reaction.

One of the major reasons for prolific development of ASR (more severe than that observed in Case Study 3) was determined to be due to the presence of numerous longitudinal and transverse long continuous cracks, not related to any specific reactive aggregate but were formed by bulk expansion during cyclic freezing and thawing of a non-air-entrained concrete at critically water-saturated conditions. Cracks formed by cyclic freezing have opened up channels for migration of water, an essential ingredient for sustaining ASR.

Expansion within the concrete substrate has placed the plaster in tension and created cracks that are wider at the trowel-finished plaster surface and taper inside.

The plaster itself was determined to be made using sound materials, following good plastering practice, did not contribute to the distress, but rather benignly responded to the internal expansion of concrete substrate by extensive cracking.

This case study indicates the importance of good quality control and assurance of not only the plaster but also the substrate on which the plaster is placed. In many case studies of plaster cracking by ASR in the substrate that the author was involved, plastering was done on substrate with no prior information about the quality and soundness of the substrate. Due to the proximity to a continuously moist environment, use of a dense, well consolidated concrete or substrate containing sound, nonreactive aggregate is essential.

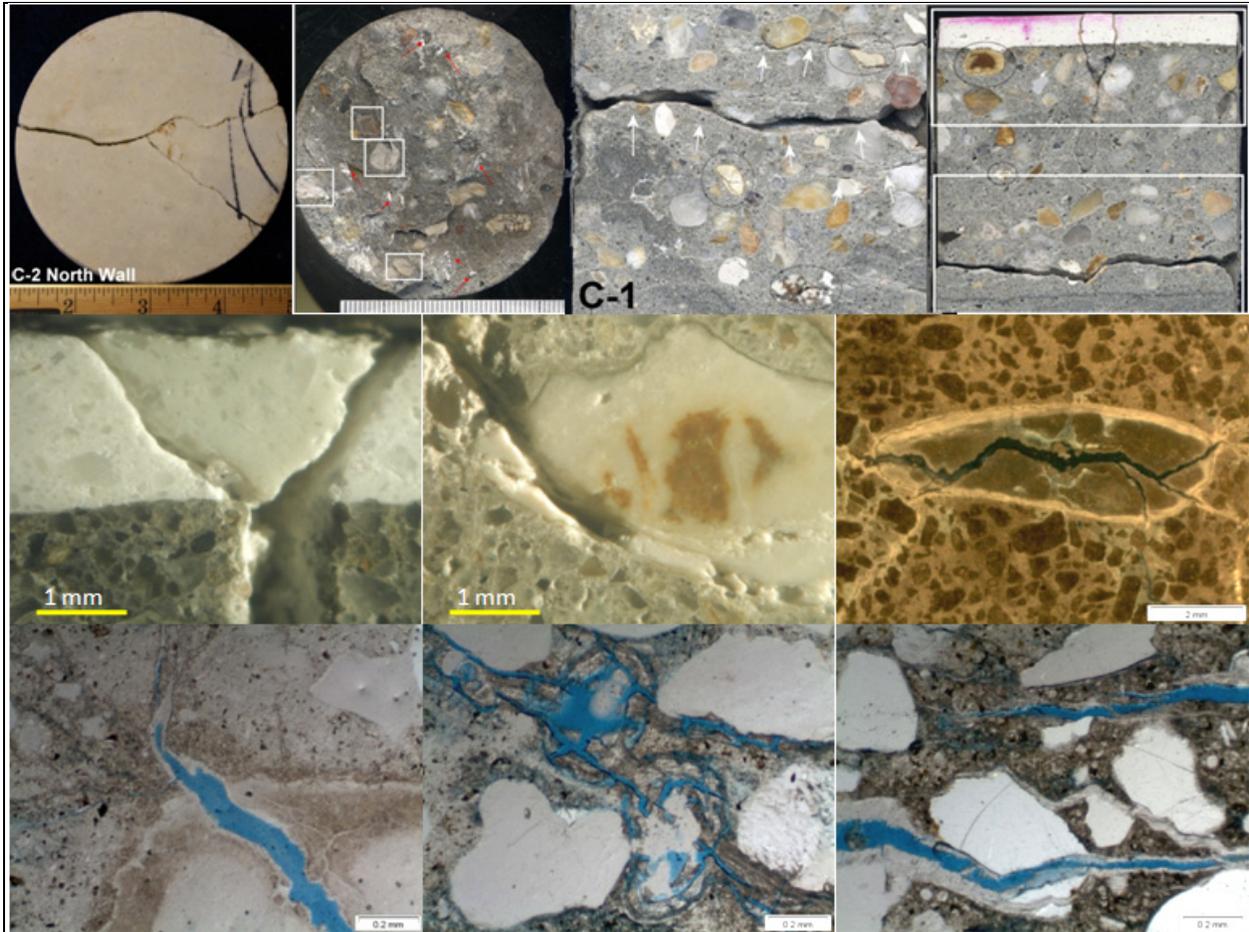


Figure 7 – Top Row from Left = Top surface of a core showing cracks; fractured surface of concrete substrate showing alkali-silica reactive chert and quartzite aggregates (boxed) and alkali-silica gel deposits in voids (arrows); lapped section of concrete substrate showing parallel cracks formed due to cyclic freezing and thawing of concrete at critically saturated conditions. Middle Row from Left = Photomicrographs of lapped cross section of the core showing cracks in plaster that have originated from the concrete substrate; cracking of an alkali-silica reactive chert aggregate in concrete; right photo shows thin section of concrete where an elliptical reactive chert aggregate shows severe cracking due to alkali-silica reaction. Bottom = Photomicrographs of thin section of core showing microcracking due to alkali-silica reaction, many originated from the reactive particle and extended to the paste; also notice alkali-silica gel deposits lining the walls of the microcracks.

Case Study 5 – Two additional Cases of Plaster Cracking due to Physical and Chemical Unsoundness in the Concrete Substrate

The following photos of plaster cracking, from two very similar case studies, show three superimposed deteriorations, all occurring in the concrete substrates that have caused cracking in polymer-modified white cement and quartz sand plasters: (a) physical unsoundness of crushed argillaceous limestone coarse aggregate particles in concrete causing expansion and fracturing, (b) alkali-silica reaction of severely strained quartz and quartzite particles in fine aggregate of substrate that have caused microcracking, reaction rims and alkali-silica gel formation in cracks and voids, and (c) cyclic freezing and thawing of concrete that was designed to be air-entrained but contained no air entraining agent. Crack patterns from these mechanisms were different but all continued to the plaster to show visible cracking. Clearly, durability of the substrate plays an important role in controlling plaster cracking. In both cases, plasters were sound and made using sound aggregates.

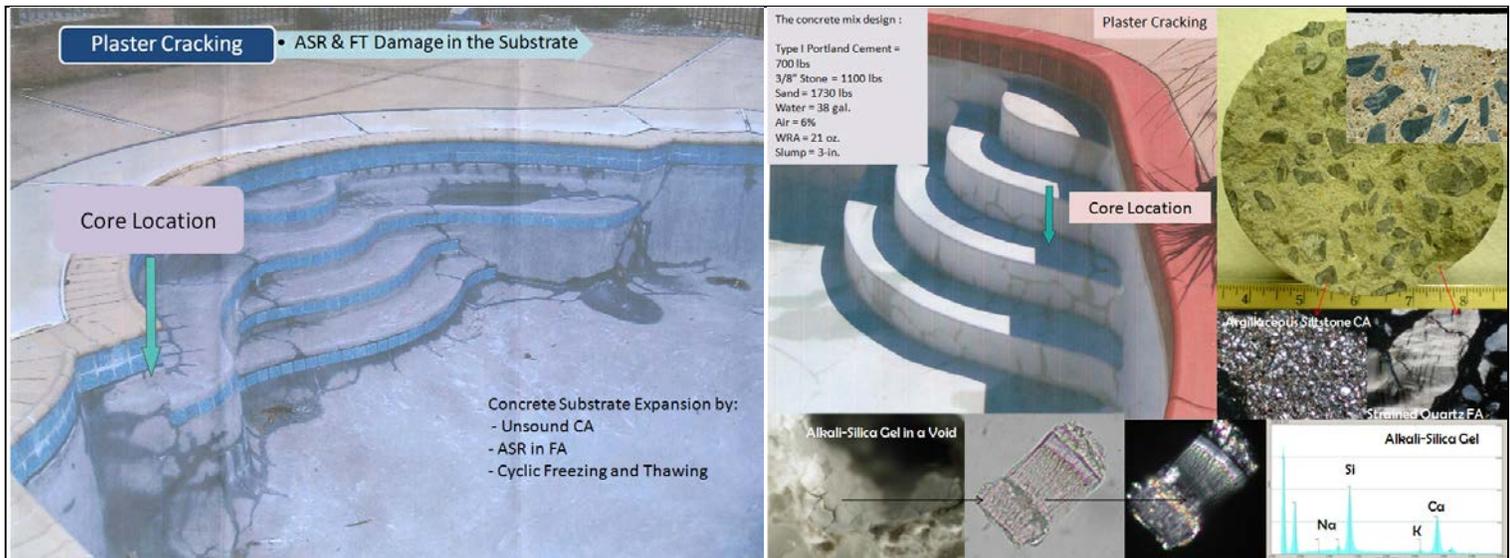


Figure 8 – Two separate pools showing cracking of pool plaster due to expansion of the underlying concrete substrate, which occurred due to unsoundness of argillaceous siltstone coarse aggregate and alkali-silica reaction of severely strained quartz-quartzite particles in fine aggregate in the concrete substrate. The right photo shows white ASR gel deposits on fresh fractured surfaces of reactive aggregates and dark reaction rims; unsound siltstone and reactive quartz particles in aggregate, white gel deposits lining the walls of voids, oil immersion mounts of gel showing its layered type birefringent nature, and EDS composition of gel having Na, K, Ca, and Si.

PLASTER DEBONDING AND DELAMINATION

Plaster debonding and delamination can occur by bond failure of: (i) the plaster from the substrate; or (ii) one coat of plaster from the undercoat [1]. Both can occur by the following reasons:

- (a) Surface carbonation of substrate or undercoat preventing development of a mechanical interlocking or bond between the two systems (plaster-substrate), or coats of plaster;
- (b) Surface efflorescence or laitance acting as a bond breaker between two components;
- (c) Too smooth and/or dense substrate or undercoat surface preventing mechanical interlocking;
- (d) Rapid drying and premature stiffening of substrate or undercoat surface;
- (e) Overly wet or water-saturated substrate or undercoat surface having water-filled pore spaces, which could otherwise be filled with finish coat or plaster for good interlocking and bond;
- (f) Rapid drying of a thin coat, especially if applied over an absorptive substrate;
- (g) The absence of a bond coat between the two plaster coats;
- (h) Delayed application of the top coat to the undercoat, or, application of a too thin top coat;
- (i) Plaster placement in a subfreezing temperature, or on a frozen substrate;
- (j) High shrinkage potential of an excessively thick coat (or excessive addition of calcium chloride in a mix) causing cracking and debonding;
- (k) The presence of oil, dirt, loose debris, acid, form-release agent, or other contaminants on a substrate or undercoat surface preventing a good contact between two components;
- (l) Improperly scratched, scored, notched or finished undercoat surface; and,
- (m) Over-troweling the finish coat of a plaster, or, troweling beyond the final set can cause delamination of the top $\frac{1}{8}$ in. of plaster.

Most of these reasons of plaster delamination can be readily diagnosed by the laboratory methods discussed in this paper.

Three terms usually referred to in connection with plaster debonding are buckles, blisters, and spalls [1]. Buckles are debonded bulges on plaster surface where coating is partially separated from undercoat or substrate but have not yet lifted off, usually due to failure of one coat to bond to the undercoat or substrate. Blisters are small round bumps on plaster surface, due to partial separation within the finish coat by trapped air during finishing, or over-troweling or other reasons. Spalls are upper layer delamination due to failure to immerse plaster underwater and/or maintain immersion after placement, abrasion, aggressive pool water attack on plaster, etc.

Case Study 6 – Debonding of Plaster Coat; Due to the Absence of a Bond Coat between the Two Plaster Coats;

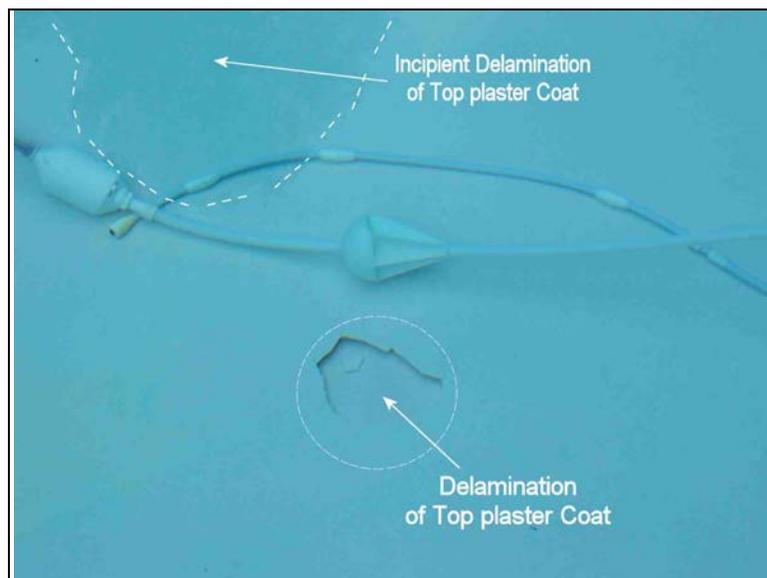


Figure 9 – Incipient and Complete Delamination of Pool Plaster.

The above photo shows an incipient and a complete delamination of the top plaster coat from the undercoat due to the absence of a bond coat between the two. A latex-modified, white portland cement plus fine sand-based pre-packaged bond coat was specified for application in between the two plaster coats, but was missed. As a result, the top coat showed “incipient delamination” (i.e., lifted off but not lost) over several broad areas (as large as 4 feet in diameter, similar to the top left corner in the photo within the dashed line), as well as “complete delamination” (i.e., lost) at isolated areas due to foot pressure (similar to the area within the circle in the middle of the photo). Moreover, the top coat applied was too thin (less than $\frac{1}{4}$ in. as opposed to $\frac{3}{8}$ to $\frac{3}{4}$ in.), which did not provide a sufficient bond strength to the undercoat. No bond coat and thin top coat – both contributed to the problem.

Case Study 7 – Debonding of Plaster Coat Due to Premature Stiffening of a Thin Top Coat

An approximately 15-year old pool was re-plastered during a renovation project, and within months of re-plastering showed various areas of delamination. Received by our laboratory were some loose pieces of debonded new plaster from the pool floor that were reportedly delaminated from the old plaster coat. The exposed surface of the new plaster showed etching and greenish discoloration from copper staining (Figure 10). The underside (i.e., the delaminated surface) showed relatively clean striated appearance, free of any contaminants, and no trace of the old plaster, indicating a clean separation of the new plaster from the old one.

The delaminated new plaster was too thin, only $\frac{1}{8}$ in. in nominal thickness, which showed evidence of rapid drying and restricted hydration of portland cement particles. The plaster was made using marble chips and white portland cement. Acid-soluble chloride analysis showed 0.126 percent chloride, by mass of plaster, which is indicative of less than one percent calcium chloride addition by mass of cement, well within the normal range, or of no addition, where chloride came from interactions with pool water. Thin section photomicrographs of plaster show surface-parallel microcracking from shrinkage and abundant residual portland cement particles and high capillary porosity in the paste in the body of the thin plaster (Figure 11), indicating premature drying prior to the immersion of plaster underwater. Debonding was judged to be due to premature stiffening and rapid drying of a thin plaster coat, which was probably overly wet and exposed to a dry or windy weather condition.

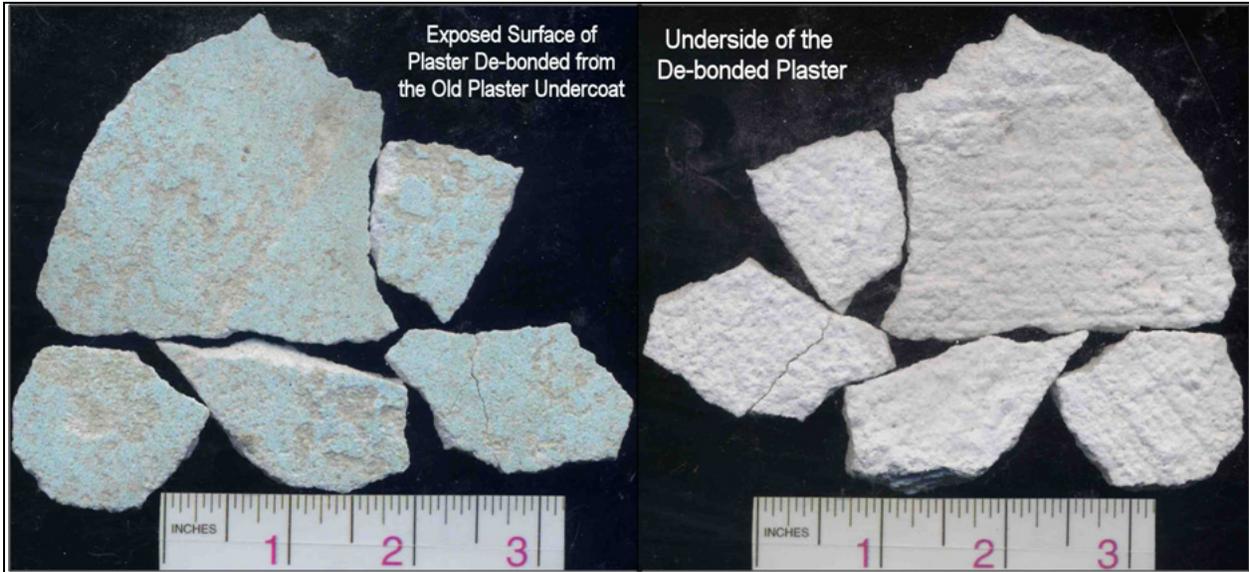


Figure 10 – Loose samples of a de-bonded plaster that was delaminated from an old plaster coat, after a replastering project. Notice the light green copper stain on the exposed surfaces of plaster pieces.

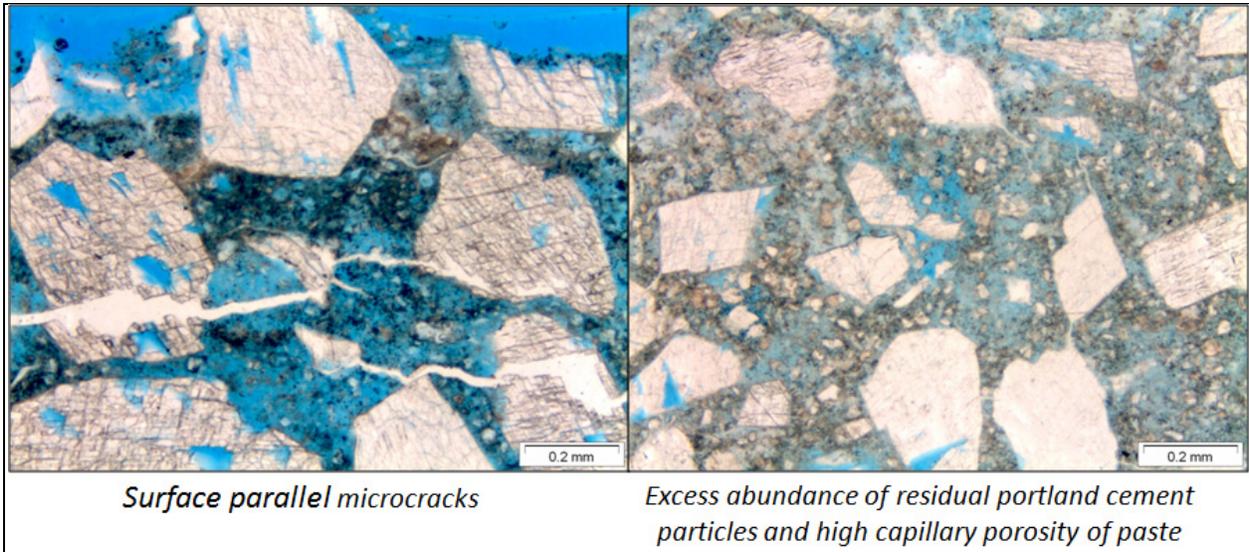


Figure 11 – Thin section photomicrographs showing microstructure of loose, debonded plaster samples. The left photo shows surface-parallel microcracks and porous paste in plaster. The right photo shows excess abundances of residual portland cement particles and capillary pores in the paste. Both features indicate premature stiffening and rapid curing of plaster.

Case Study 8 – Plaster Blistering Due to Delayed Application of the Top Coat



Figure 12 – Blistering on Plaster Surface.

Contrary to the previous case study of plaster coat delamination due to the absence of a bond coat (Case Study 6), in the present case, a latex-modified white portland cement based bond coat was applied but remained exposed to air for two weeks prior to the application of the top coat, which has changed the characteristics of the bond coat from bonding to release (usually, the top coat is recommended to be applied within 2 to 3 days of application of the bond coat). Radial cracking at the incipient blister on the left in the photo indicates an expansion of the underlying bond coat, which may have related to the release characteristics of the bond coat due to the extended delay in application of the top coat. No evidence of any potentially expansive chemical reaction was detected in the coats.

PLASTER SOFTENING

Portland cement plaster materials, and handling, mixing, and placement procedures should be in accordance with specifications and guidelines mentioned in ASTM C 926 and ACI 524. Performance and durability of plaster depends strongly on the use of proper materials, mix, placement, finishing, and curing techniques, and proper preparation of the substrate surface. Deviation from such guidelines could adversely affect the finish and performance of plaster. Possible reasons for a weak or soft plaster coating include:

- (a) Excess sand in the mix without a sufficient cement binder⁴;

⁴ Pool plaster mixes usually contain: (a) a minimum 1 part cementitious materials for every 2 parts of aggregate by mass (commonly 4:6 cement/sand mass ratio); (b) mix water content is governed by weather condition, substrate water absorption, and plaster workability, tempered water is added for facilitating placement, finishing, and curing of plaster; (c) cementitious materials to be used should meet or exceed requirements of ASTM C 150, or C 1157 for white portland cement, ASTM C 595 for blended cement, ASTM C 618 for pozzolans, and ASTM C 1240 for silica fume; and (d) calcium chloride set accelerating admixture, at approximately 1 to 2 percent by mass of cementitious materials is commonly added in liquid, flake, or granular form [calcium chloride dihydrate, $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$], fully dissolved in mix water prior to adding with cement. The uses of calcium chloride accelerator and supplemental water during troweling are common practices to prevent premature drying of rich mixes of thin plasters prior to set.

- (b) Improper sand gradation, e.g., too much fines in sand can increase the water demand and cracking potential of plaster; too much coarse in sand can reduce bond to substrate and can lower the workability;
- (c) Impurities in the sand, or, in mixing water not in conformance to the industry guidelines;
- (d) Excess mixing water;
- (e) High water-cementitious materials ratio from high water and/or low cement contents;
- (f) Addition of lime in mix, which can increase laitance and cause lime leaching in pool water;
- (g) Improper or excessive use of certain admixtures (e.g., excess calcium chloride);
- (h) Aggressive chemical attacks causing leaching and progressive weakening of plaster; and,
- (i) Placement in a subfreezing temperature, or on a frozen substrate, causing bond failure, restricted cement hydration and the resultant soft or weakened plaster.

All these above possible reasons of plaster softening⁵ can be readily diagnosed by detailed petrographic examinations, and supplemental chemical (e.g., chloride) analysis of a field sample of softened plaster. Excess sand, improper sand gradation, and impurities in sand are often best diagnosed by optical microscopy. Lime, or excess water additions are also detected by examining the textural and compositional properties of plaster paste during petrographic examinations. Acid-soluble chloride analysis of bulk plaster (ASTM C 1152) determines calcium chloride dosage and its influence on plaster characteristics. Softening by severe etching or leaching, as well as the depth of deterioration is best observed by optical and/or scanning electron microscopy. Freezing at the plastic or semi-plastic state of plaster is also best diagnosed by characteristic plastic freezing microstructures in the plaster paste in an optical microscopical examination.

ATTACK BY AGGRESSIVE POOL WATER – LEACHING, ETCHING AND SCALING

The ANSI/NSPI Standards [6] recommend the balanced pool water to have the following parameters:

Parameters	Minimum	Ideal	Maximum
Free Chlorine (ppm) ¹	1.0	2.0-4.0	10.0
pH ²	7.2	7.4-7.6	7.8
Total Alkalinity ³ (ppm, as CaCO ₃)	60	80-120	180
Calcium hardness ⁴ (ppm, as CaCO ₃)	150	200-400	1000
Total Dissolved Solids ⁵ (ppm)	300	1000-2000	2400

¹Free chlorine is the active form of chlorine that is able to destroy potentially harmful organisms in water, which is total chlorine minus combined chlorine that was used up and thus no longer has the ability to disinfect; ²pH is the acidity/alkalinity index of water, high value makes water alkaline, produces scale and reduces sanitizing capacity of chlorine, whereas low value makes water acidic/aggressive, and causes etching; ³Measure of water's resistance to change in pH, equates to the amount of alkaline substance, e.g., hydroxides, carbonates, and bicarbonates in water; ⁴Measure of dissolved calcium salts in water; ⁵The amount of total dissolved matter in water from all sources.

Pool water having chemistries within these acceptable ranges is “balanced” in the sense that the water will not attack the cementitious coating. Pool water not in the range of above acceptable tolerance or balanced as in accordance with the ANSI/NSPI standards is detrimental to plaster. The term Langelier Saturation Index (LSI), after Wilfred Langelier, is widely used to determine thermodynamic potential for a water to dissolve or precipitate calcium carbonate [7]. LSI is a measure of saturation of water with respect to calcium carbonate incorporating: pH, total alkalinity (TA), calcium hardness (CH), total dissolved solids (TDS), and water temperature (WT) as the variables ($LSI = pH + f_{WT} + f_{CH} + f_{TA} - f_{TDS}$, where ‘f’ stands for factors for different variables shown in the table below, LSI for balanced water should be as close to zero as possible with an acceptable range from -0.3 to +0.3). Depending on LSI's variation in opposite directions of the recommended levels, the pool water may get cloudy and secondary deposits precipitate on plaster surface; or, causes leaching and etching of plaster surface. The LSI chart below provides factors for different variables, to determine the pool water chemistry:

⁵ Many pool professionals prefer the term “weak” plaster rather than “soft” plaster, which, in author's opinion, conveys different meanings, i.e., weak plaster refers to a low-strength plaster, whereas a ‘soft’ plaster can have excellent strength but have low scratch hardness on the surface.

Water Temperature		Calcium Hardness		Total Alkalinity		Total Dissolved Solids	
°(F)	f _{WT}	ppm	f _{CH}	ppm	f _{TA}	ppm	f _{TDS}
32	0.0	25	1.0	25	1.4	< 1000	12.1
37	0.1	50	1.3	50	1.7	≥ 1000	12.2
46	0.2	75	1.5	75	1.9		
53	0.3	100	1.6	100	2.0		
60	0.4	125	1.7	125	2.1		
66	0.5	150	1.8	150	2.2		
76	0.6	200	1.9	200	2.3		
84	0.7	250	2.0	250	2.4		
94	0.8	300	2.1	300	2.5		
105	0.9	400	2.2	400	2.6		
		800	2.5	800	2.9		

Acidic water, i.e., water having a lower pH, lower calcium hardness, lower total dissolved solids, and lower total alkalinity than the minimum recommended limits, or soft water is *aggressive* to pool plaster, and causes plaster dissolution, leaching, and resultant *etching*⁶ of the plaster surface [8].

Alkaline water, i.e., water having chemistries in the other extreme, water carrying water-soluble salts, dissolved sulfates, chlorides, and carbonates becomes cloudy and causes *scaling, salt precipitation, efflorescence, and staining* on plaster surface [8]. Excessive precipitation of salts out of the solution can severely roughen the plaster surface, requiring acid washing, scraping, or sanding the scaly surface. Precipitation of heavy metals causes stains, and of metallic salts (e.g., carbonates of calcium and/or magnesium) causes white deposits, or scales.

Often both scaling/staining/salt crystallization and leaching/etching-type deterioration can occur on the same pool plaster, as a thin layer of deposits (usually calcium carbonate, or a mixture of calcium and magnesium carbonate deposits precipitated out of pool water, or stains from soluble salts) at the surface as a thin layer over a soft, porous, and leached (decalcified) plaster paste. The surface region of many such plaster show a thin zone of highly porous plaster paste lacking calcium hydroxide component of portland cement hydration, which is overlain by a calcium carbonate-rich layer (see the case study below). Such microstructural feature indicates fluctuating pool water chemistries from acidic (causing leaching) to basic (causing scaling) extremes in relation to being in balance with the pool plaster.

Etching of pool plaster by aggressive water is a common and a well-known mechanism of plaster deterioration. Etching creates a softened, dusty, porous, *rough*, and chalky-textured plaster surface. Depending on the degree of aggressiveness of pool water, distress can vary from minor surface softening and etching to severe loss of the plaster thickness by mass dissolution.

⁶ "Leaching" is chemical dissolution of cement hydration products in paste or any water-soluble materials by water (not necessarily aggressive water). "Etching," on the other hand, refers to leaching or dissolution of paste by aggressive water, i.e., water having low pH, low alkalinity, low hardness, etc., which dissolves not only cement hydration products from paste but, depending on the degree of acidity, can also dissolve calcareous aggregates in plaster. This difference between the modes of dissolution of materials by any water (leaching) versus aggressive water (etching) is one of the reasons for the debate centered around the spot etching (vs. spot leaching) phenomenon. Leaching does not necessarily roughen the plaster surface but makes it porous and soft by loss of mass; etching, on the other hand, roughens the surface by aggressive water attack. Plasters (or areas in a plaster) having higher water-cementitious materials ratio and higher porosity of paste are more susceptible to leaching and etching than the denser plasters (or denser areas in a plaster) having a paste of lower water-cementitious materials ratio.

During petrographic examinations, an etched plaster surface (i.e., attacked by aggressive water) appear as soft, dusty, rough, chalky-textured surface compared to the smooth sound finish, and shows increased porosity of paste and loss of cement hydration products (leaching of calcium hydroxide and decalcification of calcium silicate hydrate component of portland cement hydration) at the surface region of plaster. Carbonate aggregates near surface often show dissolution by acidic water attack. Damage by aggressive water can be best observed in a carefully prepared thin section of a plaster cross section by using a petrographic microscope, or a scanning electron microscope. Leaching (not necessarily by aggressive water) is evident by preferential dissolution of cement hydration products from near the exposed plaster surface without necessarily affecting the carbonate aggregates.

Case Study 9 – Evidence of Plaster Etching by Aggressive Water

Due to the alkaline nature of the plaster, aggressive pool water causes etching of plaster paste and carbonate aggregates. The depth and severity of etching depends on the aggressiveness of the water, the duration that the water remained aggressive, and the quality of the plaster. The following case study shows an example, where plaster surface developed broad areas of etching (see Figure 13).

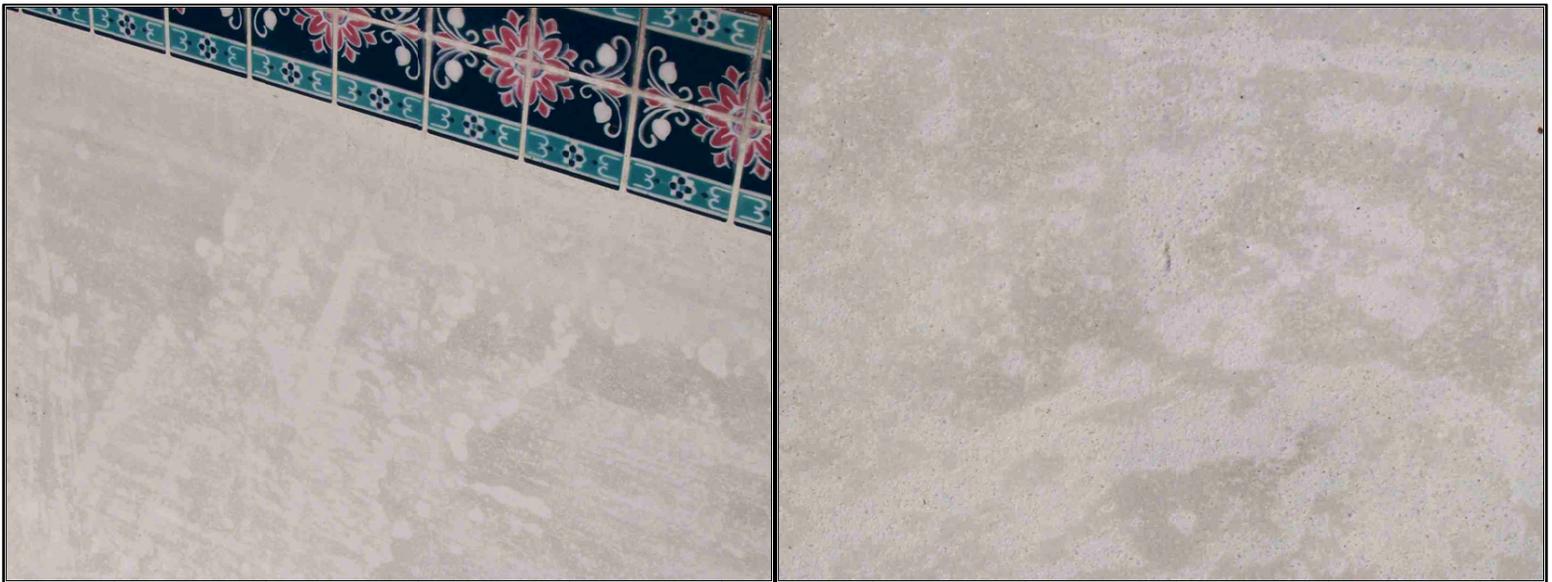


Figure 13 – Photographs of a swimming pool showing etching of plaster surface.

Core samples of plaster plus concrete substrate show evidence of plaster surface etching as darker patchy areas rich in carbonate aggregates (where the intervening paste in between the aggregate particles has been lost), and relatively lighter areas rich in leached and etched porous paste (see Figure 14). Plaster contained marble chip aggregate and white portland cement, acid-soluble chloride analysis indicated 2.6 percent calcium chloride addition.

Thin section photomicrographs of the plaster show clear evidence of loss of the paste and carbonate aggregates at the plaster surface, to a depth of 0.2 to 0.5 mm (Figure 15), and an overall porous nature of the plaster paste at the surface and down to a uniform depth of 3 to 4 mm. The total plaster thickness is 10 to 12 mm, where a denser region is present beneath the top porous region. The porous nature at the surface is clearly distinct in blue dye-mixed epoxy-impregnated thin section by a greater degree of blue dye absorption at the top 3 to 4 mm than the interior denser plaster body. Such a porous surface may indicate application of a finish coat having a higher water-cementitious materials ratio than the body, or, finishing in the presence of excess water at the surface, either of which has decreased the resistance of plaster to surface etching by the aggressive water.

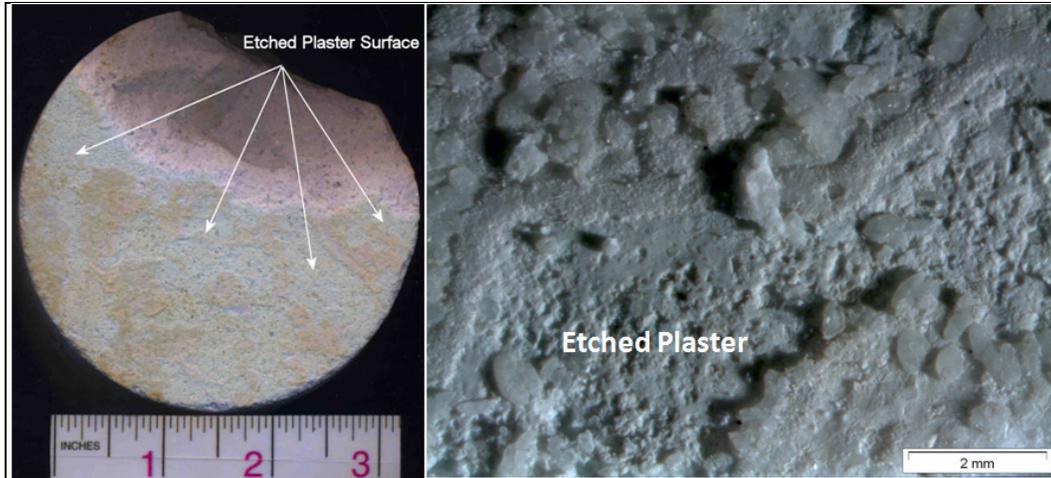


Figure 14 – Photograph of the top etched plaster surface in the core (left photo) taken from the pool shown in Figure 13, which, at a higher magnification (right photo) shows the loss of paste from around the aggregate particles, and loss of marble aggregate particles at the surface as well. The brown patchy areas are rich in aggregates and lighter gray areas are etched paste.

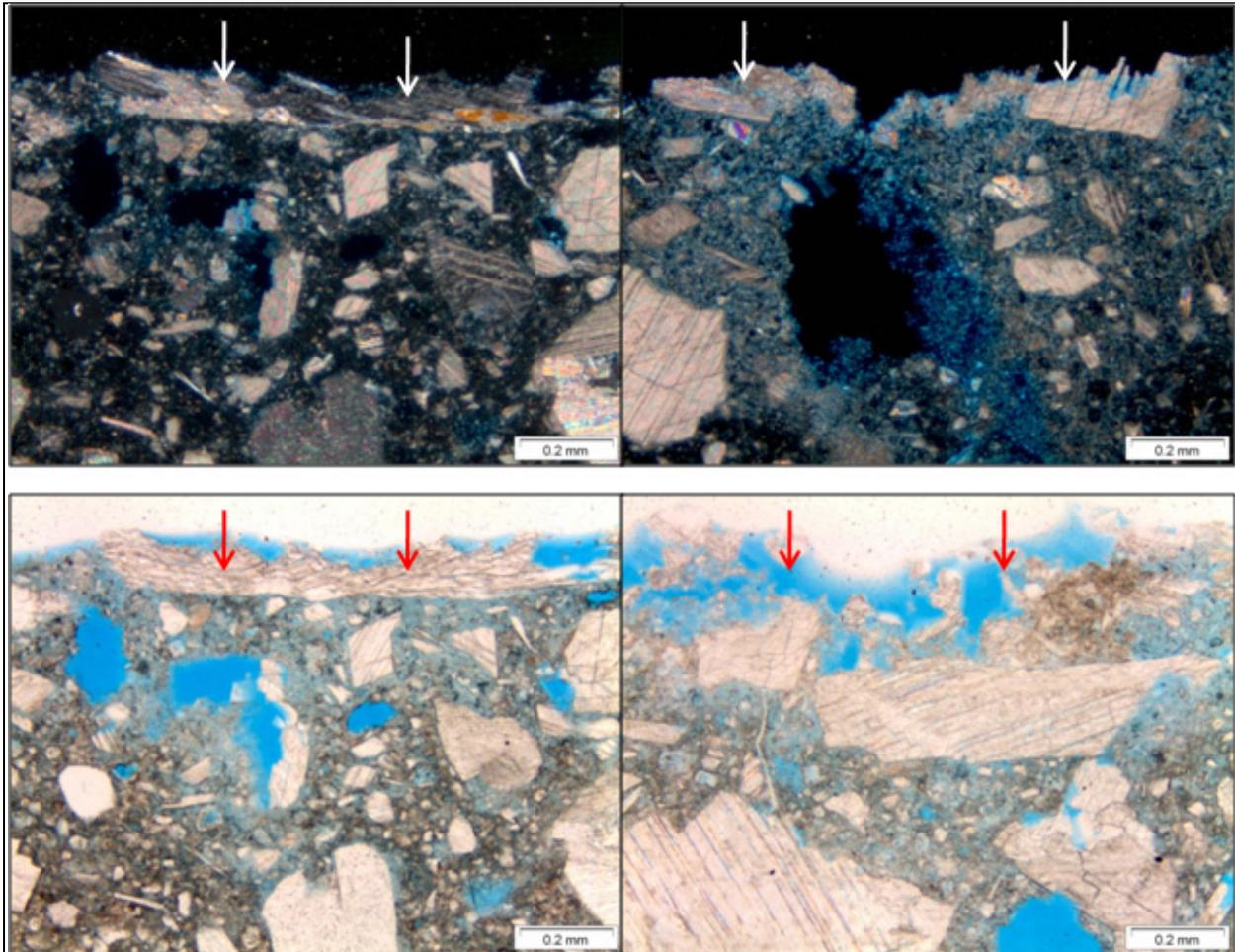


Figure 15 – Photomicrographs of blue dye-mixed epoxy-impregnated thin section of plaster showing etching of marble aggregates and paste on the plaster surface, loss of paste, and highly porous zone of paste at the top 0.2 to 0.5 mm. The porous nature of the paste at the surface region, beneath the etched plaster surface can be readily highlighted by the blue dye-mixed epoxy used for impregnating the sample prior to thin sectioning.

Case Study 10 – Secondary Calcite Precipitation on Plaster Surface – Evidence of Plaster Scaling by Alkaline Water

As the opposite extreme of etching, the following case study shows surface scaling, as secondary calcium carbonate precipitates on the plaster surface, due to the exposure of plaster to a pool water having a high pH, high alkalinity, high calcium hardness, and the presence of excess dissolved solids. The plaster surface showed dog-tooth shaped secondary calcite precipitates, 50 to 70 micron in thickness, some overlain by a relatively leached and porous paste.

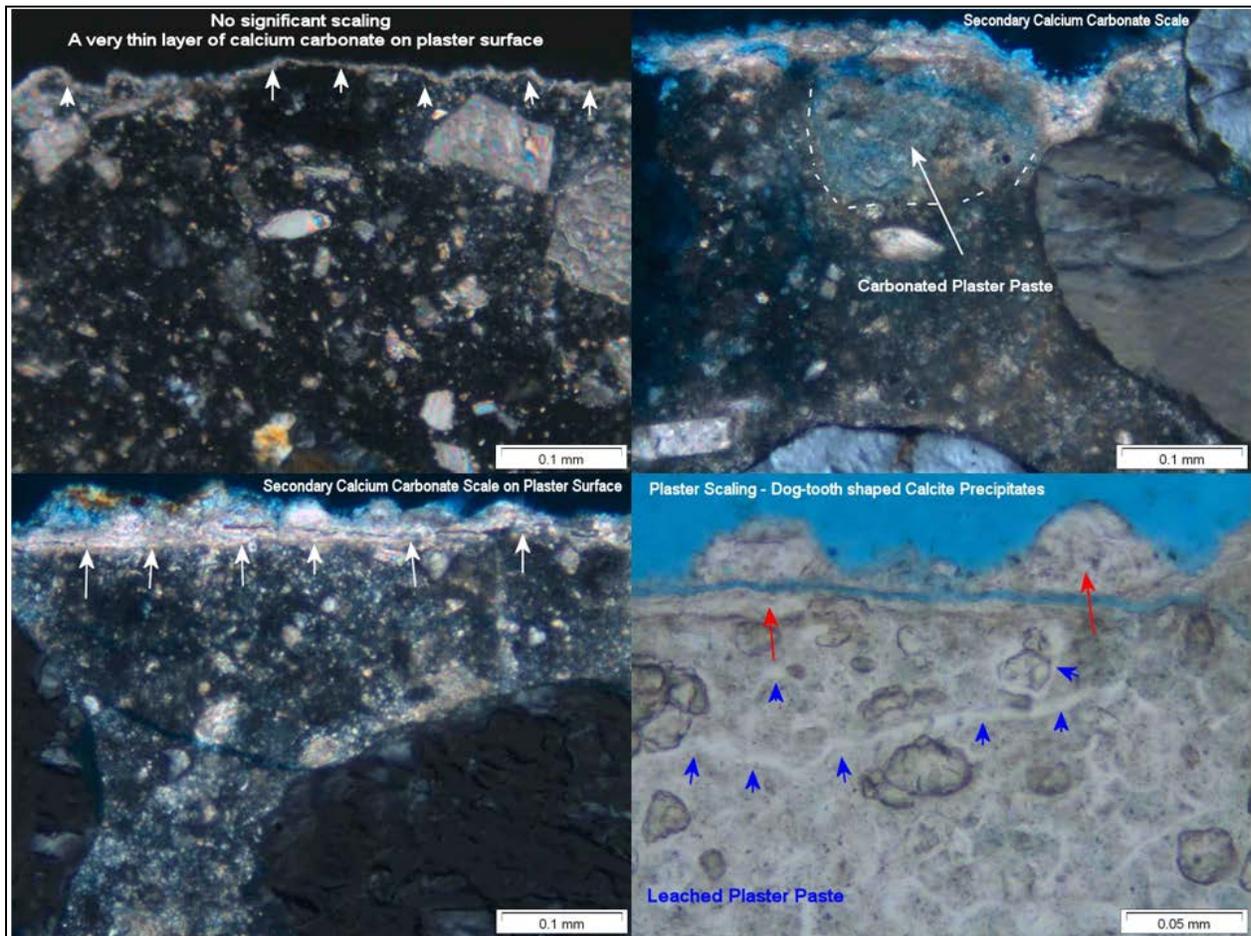


Figure 16 – Photomicrographs of thin sections of plasters showing no scaling in the top left photo versus scaling and dog-tooth shaped secondary calcite precipitates on the plaster surface in the other photos. The bottom right photo shows leaching of paste beneath the calcite scales indicating effects of a fluctuating pool water chemistry from a low pH (caused leaching) to a high pH environment (caused scaling).

The top photomicrographs are thin sections of plaster cross sections showing appearance of a scaled plaster surface. Excessive development of secondary calcium carbonate scales on the surface requires acid washing or sanding – the extent of scaling or its removal after washing can be best diagnosed by examination of thin section of plaster in a petrographic microscope.

PLASTER DISCOLORATION – SPORADIC MOTTLED AND BLOTCHY SURFACE

Rarely, a white pool plaster (also called “marcite”) is milky white in appearance; it is rather cloudy white with a normal color variation, or normal mottling, which generally has a uniform shading, blotchy or cloudy appearance across the plaster surface. Such a normal discoloration or mottled-shade variation is common and not usually considered as a failure or defect [1].

Abnormal discoloration [1], as sporadic shaded areas, excessive mottling, blotchiness, and smaller discolored, variably grayish hued areas, however, are different from normal uniform discoloration, can be a real aesthetic nightmare, and often require repair or re-plastering.

Discoloration can be due to one or more of the following reasons:

- (a) Contamination in sand, such as iron, which can cause rust stain;
- (b) Color pigment in a pigmented plaster, which is not mixed thoroughly;
- (c) Variations in water contents and water-cementitious materials ratio of the finish coat of plaster from batch to batch;
- (d) Excessive dry spots, wet spots, or uneven areas of moisture in the concrete or shotcrete substrate can affect the rate of plaster hydration, drying, and setting, and the resultant color of the plaster surface (which, depending on the area of dry or moist substrate, can show normal overall mottling, or, isolated plaster darkening, blotchiness or discoloration);
- (e) Trowel burn, either by over-troweling the finish near the final set of plaster, or troweling past the final set without supplemental moisture to lubricate the finish, can cause an aggravated form of mottling, or severe blotchiness. This discoloration is often in an arc or in the pattern that follows the trowel motion, and occurs by differential rate of squeezing mix water out of the surface by troweling pressure, and/or, from metal of the trowel being deposited onto the plaster surface;
- (f) Calcium chloride, commonly added as set accelerator and to improve plaster water tightness, early strength, and density, can alter the plaster surface coloration. Depending on the amount added, calcium chloride admixture can cause white plaster coating to exhibit a darker gray hue, and colored coating to exhibit blotchiness or mottling;
- (g) Large difference in plaster thickness can cause color variation; thicker areas are usually darker and thinner plaster appear lighter in color because thicker plaster tends to retain moisture longer, causing rate of cement hydration to be different from the rest; thinner plaster loses moisture fast, thereby affecting the rate of cement hydration and the resultant color;
- (h) Difference in moisture contents of concrete or shotcrete substrate can impart different shades of gray hues to a plaster surface, especially if the plaster is thin;
- (i) Splashing of rain or other water on a freshly placed plaster (especially in a colored plaster) that has reached the final set but has not yet been immersed in water can show color difference between the splashed area and other areas;
- (j) The presence of ground granulated blast-furnace slag as a cementitious material in the concrete or shotcrete substrate is known to impart a bluish grey to black discoloration on plaster, which can be reduced by a thick bond coat between the plaster and substrate;
- (k) Improper start-up of pool and failure to adequately brush the pool during the start-up period can impart discoloration on plaster;
- (l) Prolonged presence of pool water at a low level after a partial drainage can develop a darker hue on the aerated portion and a lighter hue on the underwater portion; and,
- (m) Corrosion of reinforcing steel in the substrate can generate rust stains, which can migrate through the substrate and plaster body to the surface of the plaster and appear as rust stains (from orange red to black) – this type of plaster stain, as opposed to other stains on plaster surface precipitated or absorbed onto the surface, comes from within or below the plaster.

Case Study 11 – Plaster Discoloration from Excessive Calcium Chloride Addition and High Iron Content in Plaster Cement

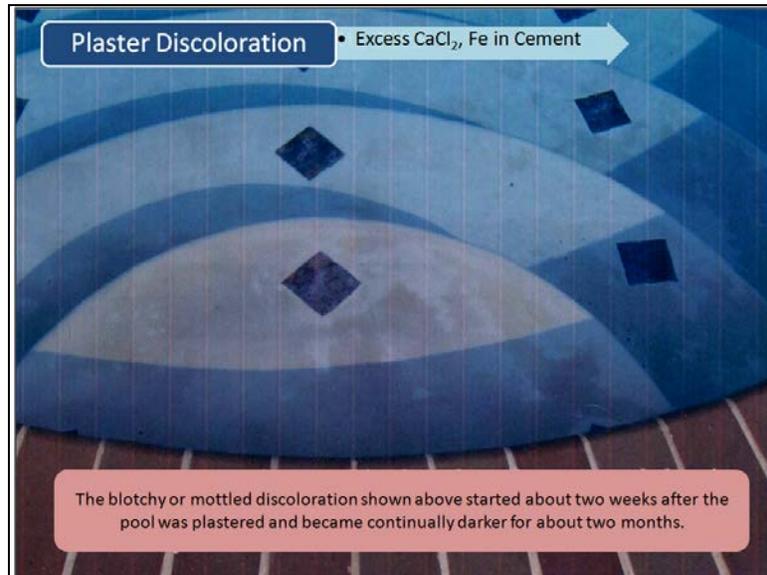


Figure 17 – Photograph of a swimming pool showing blotchy or mottled grey-hued discoloration of pool plaster over a broad area.

In order to investigate the dark gray hue mottled or blotchy nature of discoloration of the above-pictured pool, a core sample was examined that contained a $\frac{1}{2}$ in. thick plaster intimately bonded to a $6\frac{1}{2}$ in. thick shotcrete substrate. Acid-soluble chloride content of the plaster was 1.03 percent by mass of bulk plaster, which corresponds to a 5.3 percent addition of calcium chloride by mass of cement, well in excess of the standard limit of 2 percent. Calcium chloride admixture is known to impart a grayish hue discoloration on pool plaster, which was determined to have caused blotchy discoloration in the above pool as well. In addition, the white portland cement paste in the plaster showed an unusually high amount of ferrite phase, which also imparts a darker hue from delayed hydration of ferrite phase in the presence of excess calcium chloride (which explains the reported progressive darkening of the pool plaster with time). Discoloration reportedly occurred in a number of other pools as well, which were constructed with the present one by the same plasterer, after a change of the cement source. The evidence is consistent with the observed high iron content in the residual portland cement particles detected in the present sample being a possible reason for plaster discoloration. No evidence of leaching or etching of plaster paste was found, rather a thin layer of calcium carbonate deposit was noticed, as scale from alkaline pool water.

Case Study 12 – Discoloration due to Prolonged Low Level of Pool Water

The following type of plaster discoloration (see Figure 18), from a uniform grey-hued top portion to a cloudy white bottom is very common in many pools, which is due to prolonged settling of pool water at a low level after a partial drainage (which was during the entire winter season in this case), where portions remained underwater appeared lighter in color than the aerated portion of the pool. The aerated portion, being drier than the underwater portion appeared as a darker shade.



Figure 18 – Darker versus lighter gray discoloration of aerated and underwater portions of a pool.

Case Study 13 – Discoloration due to Differential Moisture Contents of Plaster and/or Substrate

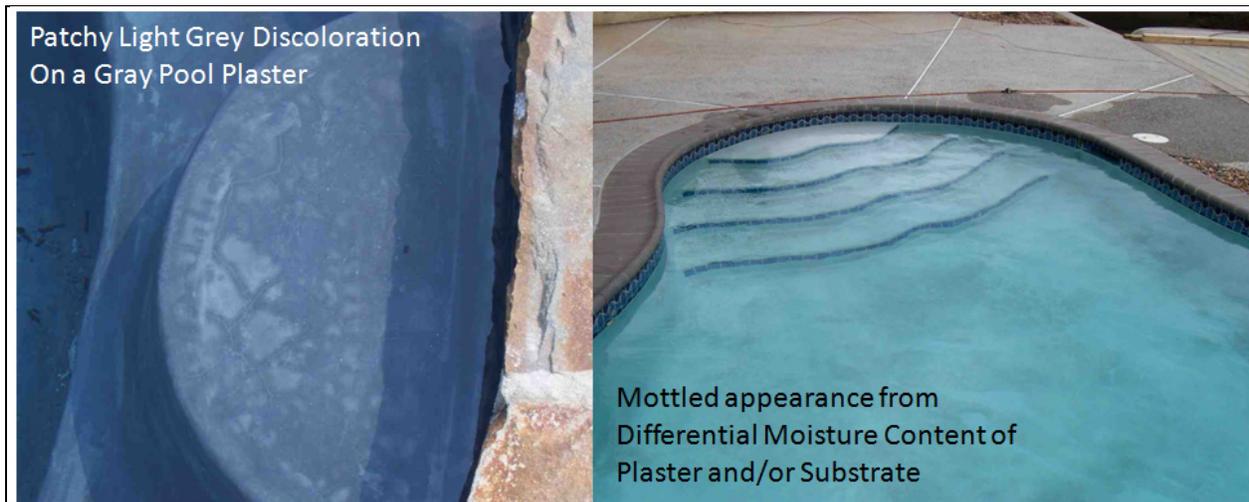


Figure 19 – Mottled Discoloration of Pool Plasters.

The left photo shows a gray pool plaster (prepared by using a normal grey Type I portland cement, black plaster sand, and a liquid dye), which developed normal early shrinkage cracks after application. The cracks remained open underwater, pool water entered through those cracks, caused leaching of paste from around the cracks, and as a result, increased paste porosity adjacent to the cracks. The porous areas of paste adjacent to the cracks appeared lighter grey in shade than the overall darker gray color of the denser plaster in areas away from the cracks. The right photo shows general overall mottled discoloration in a pool where the pool plaster has had an acceptable amount of calcium chloride admixture. The plaster was applied on a shotcrete substrate, which is usually more porous and absorptive than a concrete substrate. Differential moisture content of the plaster and/or substrate is mentioned by many pool professionals to be the reason to impart such a mottled appearance.

STAINING DISCOLORATION

Staining, as opposed to sporadic mottling or gray-hued blotchiness, commonly occur in localized areas, and is distinct in color from the rest of the plaster surface. Staining discoloration is caused by precipitation, leaching, or absorption onto a plaster surface by one or a combination of the following:

- (a) Heavy metal minerals come out of pool water solution and precipitate on the plaster surface as inorganic stains; common examples of such stains and the source metals are [8]:

Metal	Source	Stain on Plaster
Calcium	Plaster, grout, Mortar, Cal-hypo chlorine shock	White scales of calcite
Cobalt	Fiberglass shells	Red, blue, gray, black
Copper	Copper Algaecides, ionizers corrosion of copper and brass pipes, fittings, heat exchangers of pool heaters	Blue, green, blue/green, black, dark red, teal
Iron	Well water, corrosion of iron pipe and fittings	Dark red, brown, black, gray, green
Manganese	Well water	Pink, red, black

- (b) Water spills or splashes after final set before immersion in pool water;
- (c) Stains by certain metal, mineral, organic or inorganic materials – either after the final set prior to immersion in water, or, underwater by dissolution, oxidation, or other reactions with pool water and/or cementitious plaster;
- (d) Oils or dirt from human and/or pets;
- (e) Precipitation of calcium, iron, or some mineral (e.g., in fertilizers) or metals (e.g., in algaecides) shown in the above table;
- (f) Efflorescence, by migration of soluble salts from within the body of plaster underwater and deposition on plaster surface, especially noticeable on colored plaster surface;
- (g) Water, oil, or dirt drip lines that are not washed off from the cleaning of tile or pool deck; Drip stains from brick masonry coping around the plaster; and,
- (h) Organic deposits such as algae and bacteria can discolor pool water and precipitate on plaster surface as green, black, yellows, pink deposits, which are distinguished from metal/mineral stains in that they are on the surface and do not penetrate into the plaster.

Figure 10 shows characteristic green stain on pool plaster from copper (which comes from copper algaecides or degradation of copper pipes or heat exchanger in pool heater in a high chloride and/or low pH pool water).

Case Study 14 – Staining of Brick Mortar Coping from Manganese in Bricks

The brick-masonry coping of a swimming pool showed dark gray to brown discoloration of jointing mortars, causing drip stains on plaster surface from the mortar joints. Brick units were brown, solid, clay-fired masonry, containing dark brown glassy aluminosilicate matrix, fine (< 1 mm size), angular quartz and feldspar grains, and dark brown to black grog of ferruginous materials. Jointing mortars are non-air-entrained and made using portland cement, sand, and a polymer binder. Elemental analyses of jointing mortars from stained areas show a marked enrichment of manganese in the stained mortars, having maximum concentration at darkest stained areas adjacent to bricks, an element, also detected in the adjacent bricks. Migration of manganese from bricks to the adjacent jointing mortar by splashing of the pool water has caused the stain. Manganese is common in many clay fired bricks that can cause similar staining in masonry coping or pool plaster.

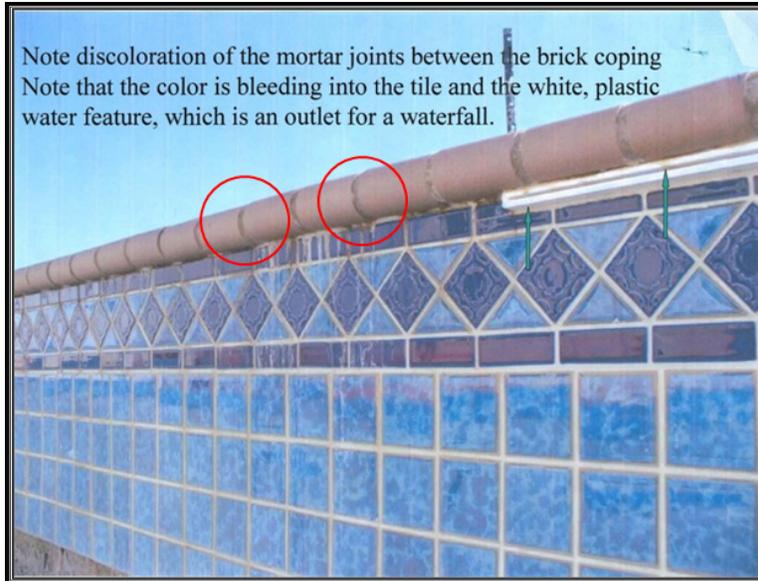


Figure 20 – Dark brown stain on mortar joints (circled) from migration of manganese in bricks.

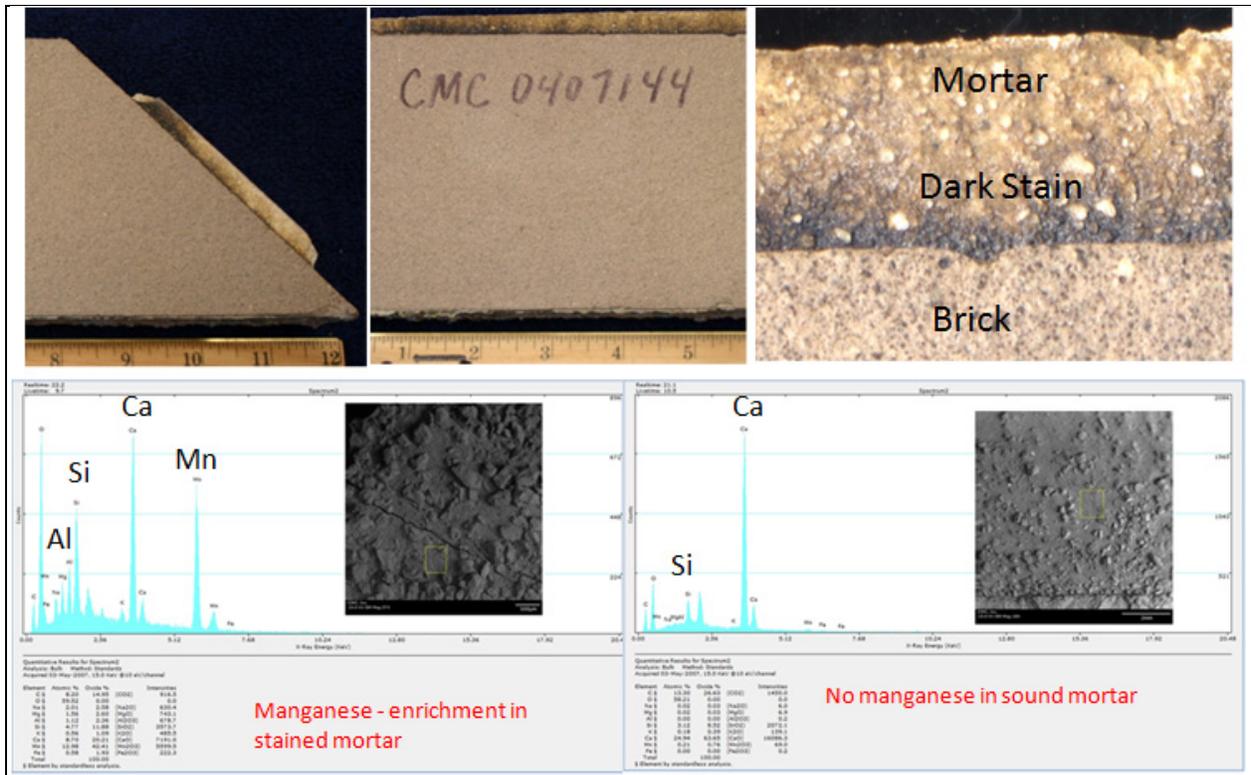


Figure 21 – The top row photos show the dark stain on jointing mortars, which have prompted the investigation. The bottom rows show manganese (Mn) enrichment in the stained mortar and its absence in the sound mortar, where Mn was derived from the adjacent bricks.

SPOT ALTERATION, SOFT (POROUS) SPOTS (SPOT LEACHING VS. ETCHING)

Beginning in the mid-1960s, and specially in the 1980s, a phenomenon then called “spot etching” received much attention in the pool industry and created significant debates among various pool professionals (e.g., NPC, onBalance, Arch Chemical⁷). Since then, there has been an increasing occurrence of this controversial and highly discussed type of plaster surface deterioration, which is reportedly characterized by:

- (a) Small, frequently round in shape, dime-sized spots ($1/8$ to $3/4$ in. in size, more commonly $1/4$ to $1/2$ in. in size), much lighter or whitened in color than the surrounding areas of the plaster, sometimes as discolored stains (tan or aqua by absorbing dissolved iron or copper from solution);
- (b) Sometimes follows the edge of tile, troweled arcs, highlighting plaster cracks, or outlines low spots in the plaster;
- (c) Characterized by soft and porous but relatively smooth plaster surface at the spots (even though some spots show aggregates exposed); and,
- (d) Areas of plaster around the spots are smooth, dense, and intact.

According to the latest version (5th edition, 2005) of the technical manual of the National Plasterers Council, spot etching is a “slang” term originating in the swimming pool plastering trade that denotes a type of etching deterioration of the surface of a cementitious coating by chemical attack. Therefore, no separate discussion of spot etching is given, and rather included under the general “etching deterioration,” indicating its origin from aggressive pool water attacks.

The term “spot etching,” according to many professionals (e.g., onBalance, www.poolhelp.com [9]), is indeed a misnomer since the deterioration does not show any “etching,” i.e., overall dissolution of plaster by aggressive water (which would be expected to be more widespread and uniform rather than localized spot-like manner), but can occur in a balanced water environment as well. Moreover, the spot surface appears as smooth in touch as in other areas, and areas away from spots are usually smooth and dense with no etching by aggressive water. Usually, there is some softening of paste with increased porosity at the discolored spots, for which, some prefer the term “soft spots” [9].

The term “spot alteration,” in author’s opinion, is broad, encompassing the “etching” versus “leaching/softening/staining” debate. The author prefers the term “spot alteration,” or perhaps, “spot leaching” (and spot staining, if spots are stained).

The cause of spot alteration, therefore, has polarized pool and spa professionals for years [9, 10]:

- (a) The service and chlorine industries (including researchers of onBalance) believe materials (i.e., excess calcium chloride in plaster) and improper troweling techniques are at fault, while
- (b) Plasterers (including researchers at NPC) mention aggressive water chemistry as the culprit.

The polarization, in author’s opinion, is guided more by debates from opposing professionals than by opposing science armed with valid sets of good data.

Researches in favor of materials and/or troweling improprieties (e.g., those conducted by onBalance, [9]) indicate no evidence of “etching” at the spots by aggressive water, or, more importantly, no etching in overall plaster or areas away from the spots, as would be expected if caused by aggressive water attack, but selective leaching, increased porosity, and softening of paste at local spots caused by a combination of improper plaster mix and over-troweling, in a sequence of events, i.e.:

- (a) Use of excessive calcium chloride set-accelerating admixture in the plaster mix (almost all case studies of spot alteration by onBalance consultants reportedly contained excess calcium chlorides in plasters), which increases shrinkage potential, porosity, and microcracking in plaster paste, and subsequent weakening of aggregate-paste bonds by paste shrinkage;

⁷ See www.poolhelp.com for research conducted by onBalance, and www.npconline.org for research conducted by NPC.

- (b) Over-troweling of surface, which brings plaster aggregates near surface, further weakens aggregate-paste bonds, and opens channels for water entrance;
- (c) Splashing of water during troweling, which increases water-cement ratio and porosity of paste at and around weakened near-surface aggregate-paste bonds, and, upon drying, deposits calcium hydroxide (readily soluble in pool water) in the porous zones;
- (d) Selective leaching of soft, porous paste underwater from areas of weakened near-surface aggregate-paste bonds (around aggregate tips) and its progressive increase of leaching laterally around the aggregates through porous paste as spots;
- (e) Eventually, continuation of similar process of increased paste porosity and thereby selective leaching and softening of paste in any other areas of local high water-cement ratio, or water entrance pathways, such as cracks, paste-plastic fitting, etc.;
- (f) Whitening of spots is due to increased porosity and softening of paste by selective leaching (and decalcification) of paste at the local spots (i.e., at and around the tips of exposed aggregates in spots, or at cracks) than at other areas; and,
- (g) Being more porous than elsewhere, spots are more receptive to form stain from absorption of metals on the soft surface than elsewhere, thereby sometime giving tan or aqua tint.

On the other hand, researches conducted by NPC (by California Polytechnic State University, Cal Poly, [10]) in the controlled pool plaster environments showed nearly 12 times more spot etching by aggressive water than that introduced by balanced water (which, in author's opinion, also indicate that balanced water also does cause spot alteration, which may have been aggravated by aggressive water). NPC/Cal Poly researchers did not document any significant effects of excess calcium chloride, hard troweling, and water supplementation on spot alteration. Questions have risen regarding whether their research documented (or addressed) general etching-type deterioration or special dime-sized spot alteration-type deteriorations, and addressed reasons for spot-like nature of deterioration.

A recent experimental study of spot alteration by Rothstein et al. [11] funded by NPC (including Cal Poly researchers) showed deterioration by aggressive water attack (especially from excessive dosage of trichloride sanitizer), which started with the dissolution of calcium carbonate from the finished plaster surface, with progressive increase in the size and depth of areas of spots as pitting, discoloration, increased carbonation, and depth of calcium hydroxide depletion from the plaster paste, and eventual coalescence of large spots into broad areas of deterioration. Their work showed dissolution of calcium hydroxide component of cement hydration from the plaster paste by water, similar to regular etching, as well as etched aggregates on small spot-size scale, and, secondary calcium carbonate precipitation on etched aggregate and spot, indicating fluctuating water chemistries from acidic to alkaline. High chloride levels at their spots are indicative of possible chloride-induced increased rate of dissolution of calcium hydroxide from paste [11]. In their study, more spot alteration occurred in the plasters containing no CaCl₂ admixtures than the ones having CaCl₂ – indicating no influence of CaCl₂ addition in spot alteration⁸ (see Table 1). Their SEM studies of field pool plaster samples of spot alteration show enriched copper (along with barium and phosphorus) deposits on the green discolored spots.

Pool	CaCl ₂ Addition (%)	Trichlor Addition	Spot Alteration			
			Number	Size (microns)	Depth (microns)	Rank (Degree of Damage)
1	2	Balanced	0	0	0	1 (Least Damage)
3	0	Aggressive	7	3000	800	3 (Severe Damage)

Table 1 – A summary of the research done by Rothstein et al. [11] showing more spot alteration in the pool made using plaster containing no CaCl₂ in the mix and exposed to aggressive trichlor dosage than the one having CaCl₂ in the plaster mix and balanced trichlor dosage. The data indicates the influence of trichlor sanitizer dosage, and no influence of calcium chloride addition on spot alteration.

⁸ Excess CaCl₂ addition, however, could increase the potential for shrinkage cracking, and, thereby, provide pathways for entry of chemicals.

Research by Arch Chemical's Water Products division [12, see Figure 22] showed that high levels of cyanuric acid stabilizer can cause over-stabilization of pool water and shorten the life of plaster finishes, even in a balanced water pool⁹, and can generate spot deterioration. Their research shed new lights on spot alteration of pool plaster by specific localized high concentration of stabilizers in the pool water, their precipitation on plaster surface as local spots, and progressive development of spot leaching by localized high chlorine and acidic environments on the plaster surface, which increases rate of leaching of plaster on small spots.

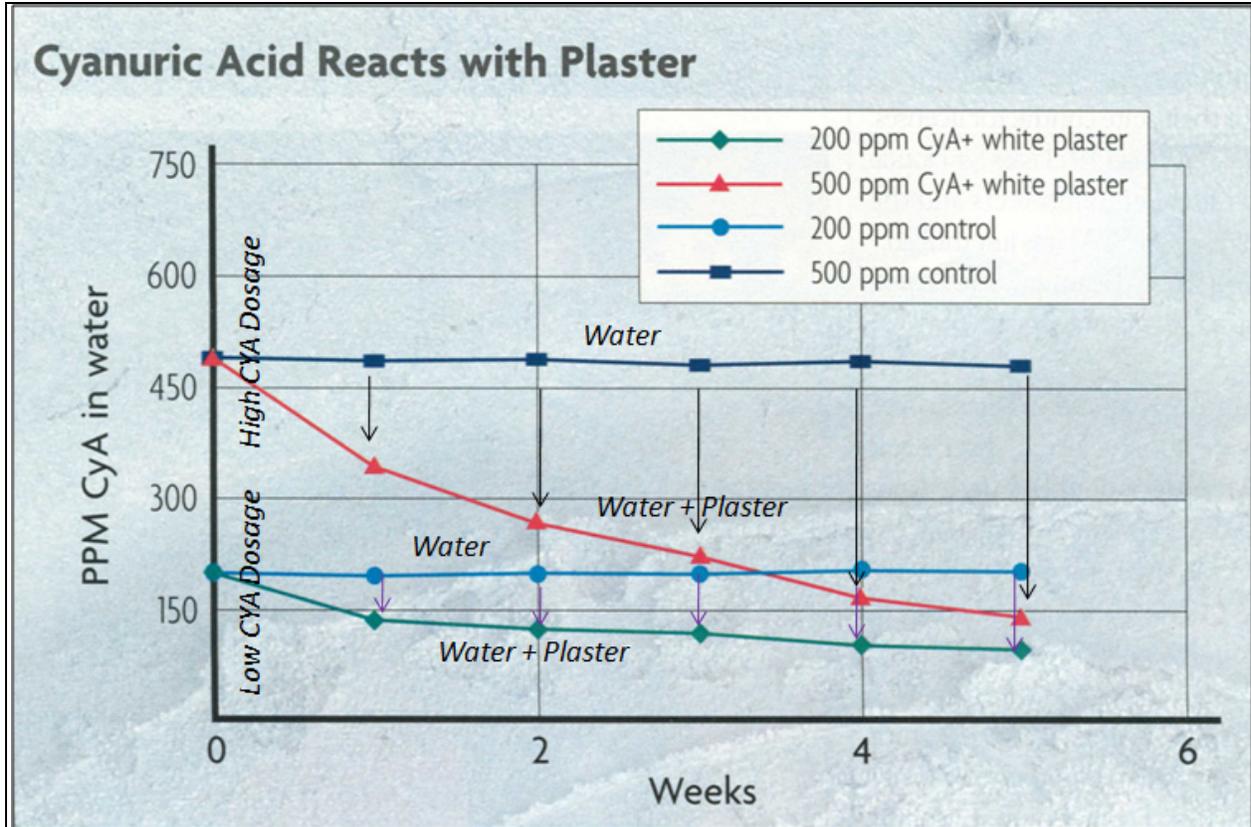


Figure 22 – Arch Chemical's research [12] showing reaction of cyanuric acid with pool plaster, which increases with time in weeks, and dosage.

Both studies by Rothstein et al. [11] and Arch Chemical [12] show the influence of pool stabilizers (i.e., trichlor, CYA, which have high chloride and low pH characteristics) on spot alteration. Based on these studies, spot alteration may indicate an early stage of more advanced etching of pool plaster, if the pool water remains over-stabilized by excessive dosage of chemicals.

⁹ Various chlorine-based sanitizers/disinfectants that release hypochlorous acid (HOCl), the active sanitizing agent to kill harmful microorganisms in pool water are sodium hypochlorite (liquid, 10% chlorine), lithium hypochlorite (granular, 35% chlorine), calcium hypochlorite (granular, 65% chlorine), and trichlor (tablet or granular, 90% chlorine), etc. Trichlor is very acidic (pH 2.8), must be dispensed with a feeder, and is known to cause spot etching problem from cyanuric acid that it contains. Dichlor and trichlor are two granular stabilizers, fast and slow-dissolving, respectively, both of which contains chlorine and cyanuric acid. Cyanuric acid [CYA, (CNOH)₃] is a stabilizer/conditioner used to resist chlorine loss in outdoor pools from UV-rays of sunlight by reacting with chlorine to produce dichloro CYA.

Case Study 15 – Spot Alteration (Spot Leaching, Pitting, and Staining)

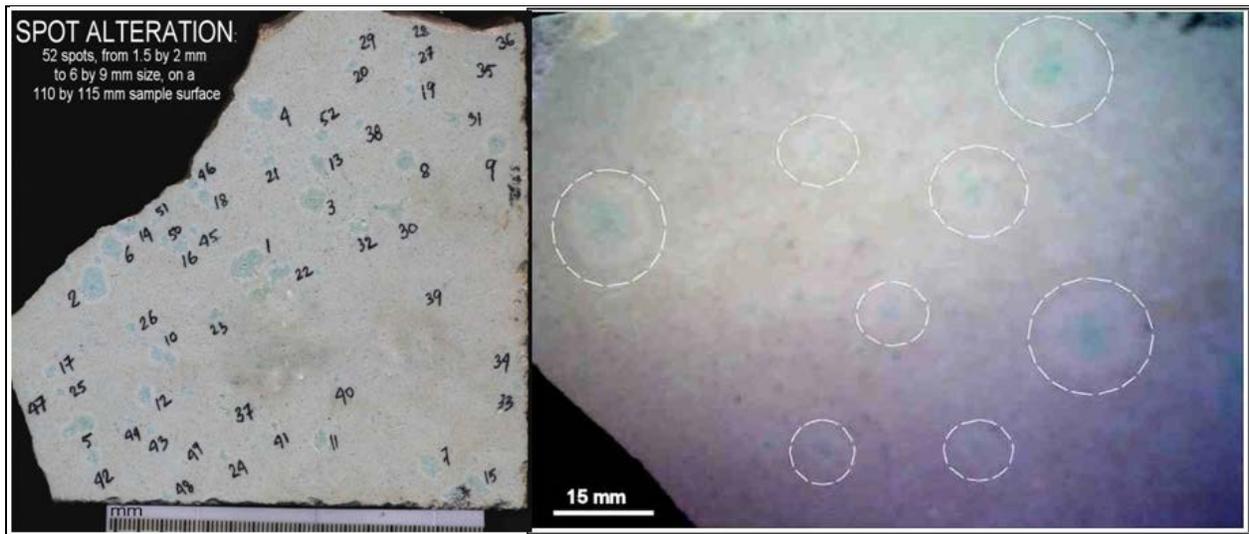


Figure 23 – Photographs of a plaster sample showing spot alteration. The left photo shows 52 spots of different sizes (from 1.5 × 2 mm to 6 × 9 mm) over an area of 110 × 115 mm. The right photo is an enlarged view showing spots having green stained cores and white rims.

All of the author's case studies on spot alteration in field plasters, including the one presented here (Figure 23), characteristically showed:

- (a) Overall smooth (on touch), soft, porous, and leached pastes at the spots, having sizes from less than $\frac{1}{8}$ to $\frac{1}{2}$ in.;
- (b) Common small pitting of the plaster surface preferentially inside the spots (Figure 24);
- (c) Dusty appearance of paste in between the aggregate particles on the spot (Figure 24);
- (d) Localized leaching of plaster paste beneath the spots, and no leaching of paste in areas in between the spots (Figures 26 and 27),
- (e) Microcracking in plaster, frequently associated with the leached paste beneath the spot (Figures 26 and 27);
- (f) Staining on spots for preferential heavy metal precipitation on porous paste (Figure 25);
- (g) Occurrences of spot etching on plasters containing normal dosages of calcium chloride admixtures; and,
- (h) Overall smooth appearance of plaster in areas away from the spots and no evidence of plaster etching (e.g., of aggregates) either on the spots or in areas away from the spots.

In the example shown here, 52 spots of shapes from circular to elliptical to irregular, and sizes from 1.5 × 2 mm to 6 × 9 mm are found on a 110 × 115 mm surface (Figure 23). Centers of the spots are stained green with copper and phosphorus enrichment, which are surrounded by white rims due to the porous nature of paste, and then normal dense, sound, smooth plaster (having no Cu or P signature) away from the spots. The green stains are from preferential absorption of copper and phosphate salts in pool water by the soft porous paste, where copper was introduced from copper algacides. X-ray elemental analyses of spots, as shown in Figures 25 and 29, also indicated an enrichment of chlorine at many spots, which are not found in areas away from the spots (similar chlorine enrichment in spots was also mentioned by Rothstein et al., [1]).

No evidence of wide-scale etching deterioration by aggressive water attack (such as the one shown in Figures 13, 14, and 15) was noticed either on the spots, or, especially in other areas of smooth plaster away from spots. The spots, however, as mentioned, show distinct preferential pitting of soft paste surface, mainly on spots having sizes larger than 2 mm, as shown in Figure 24 below. The photos also show the dusty appearance of paste on the pitted spots and stained nature of the pitted and dusty surface, indicating leaching and pitting occurred prior to staining. Spot leaching may have preferentially occurred at the inherent porous locations within the surface of the plaster, or, leaching by an external chemical on small spots may have caused porous paste at the spots; preferential staining on soft spots has occurred from water carrying heavy metals and salts.

Acid-soluble chloride analysis of the bulk plaster showed 0.286 percent chloride by weight of plaster, or, $\sim 1\frac{1}{2}$ percent CaCl_2 addition, which is well within the usual dosage of CaCl_2 admixture, indicating spot etching, in this case, was certainly not due to addition of excess CaCl_2 in the plaster mix. As mentioned, author's many other cases of spot alteration also showed no evidence of excess CaCl_2 addition.

Scanning electron microscopical examinations show evidence of leaching of calcium hydroxide from plaster beneath the spots, and precipitation of secondary calcium carbonate deposits on the surfaces of some samples by the fluctuating water chemistries. Scales, when found, however, occurred not only over the spots but in other areas as well, as thin (less than 50 micron in thickness) carbonate layers.

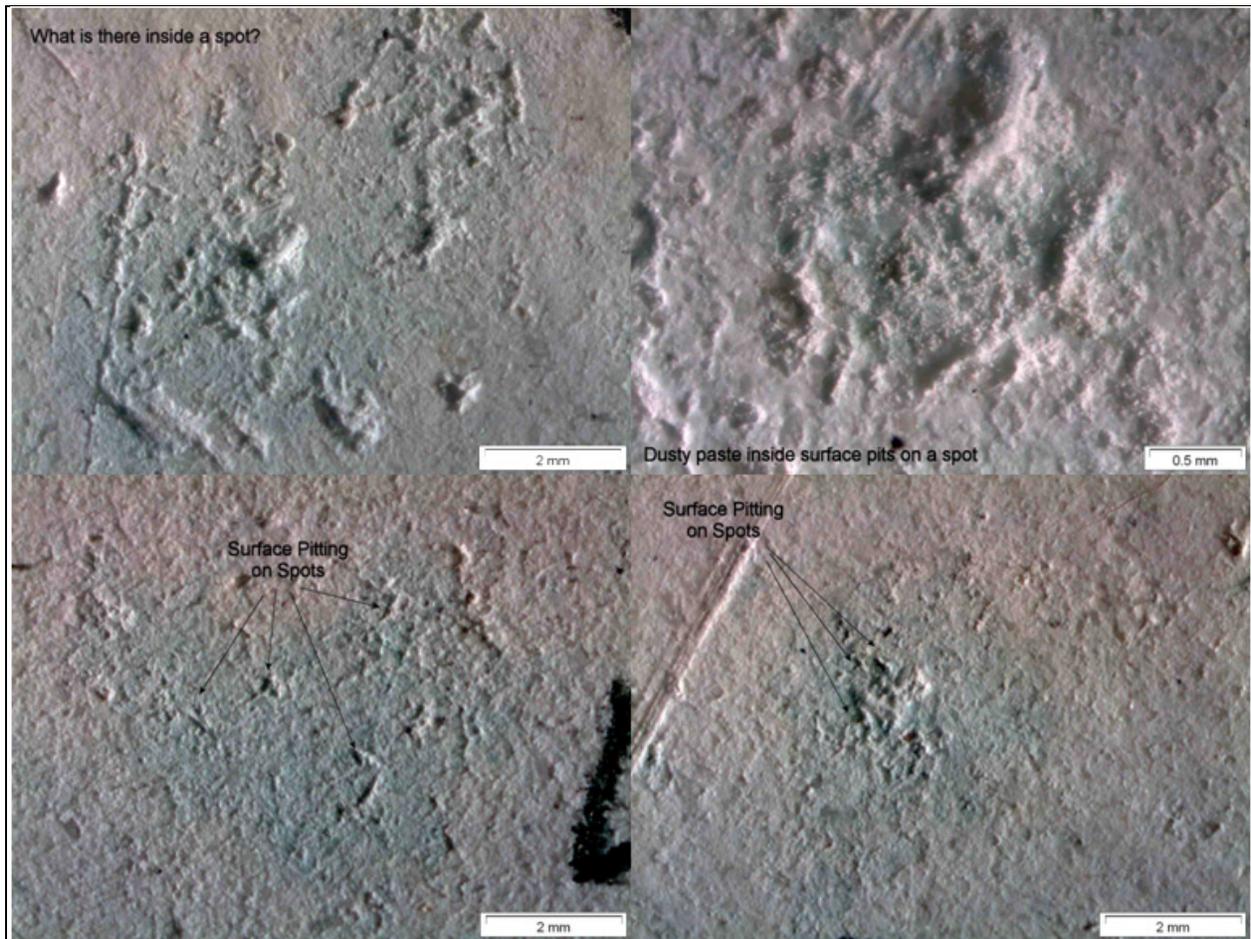


Figure 24 – Photomicrographs of plaster surface on and around the spots (taken by using a stereo microscope at a magnification of 10X) showing small surface pitting and leaching of paste on the spots, dusty appearance of paste around the aggregate particles on the spots, and greenish stains due to preferential enrichment of copper at the spots. Note the surface pitting at the spots are characteristic, occurred in almost all the spots and are not so evident in areas away from the spots.

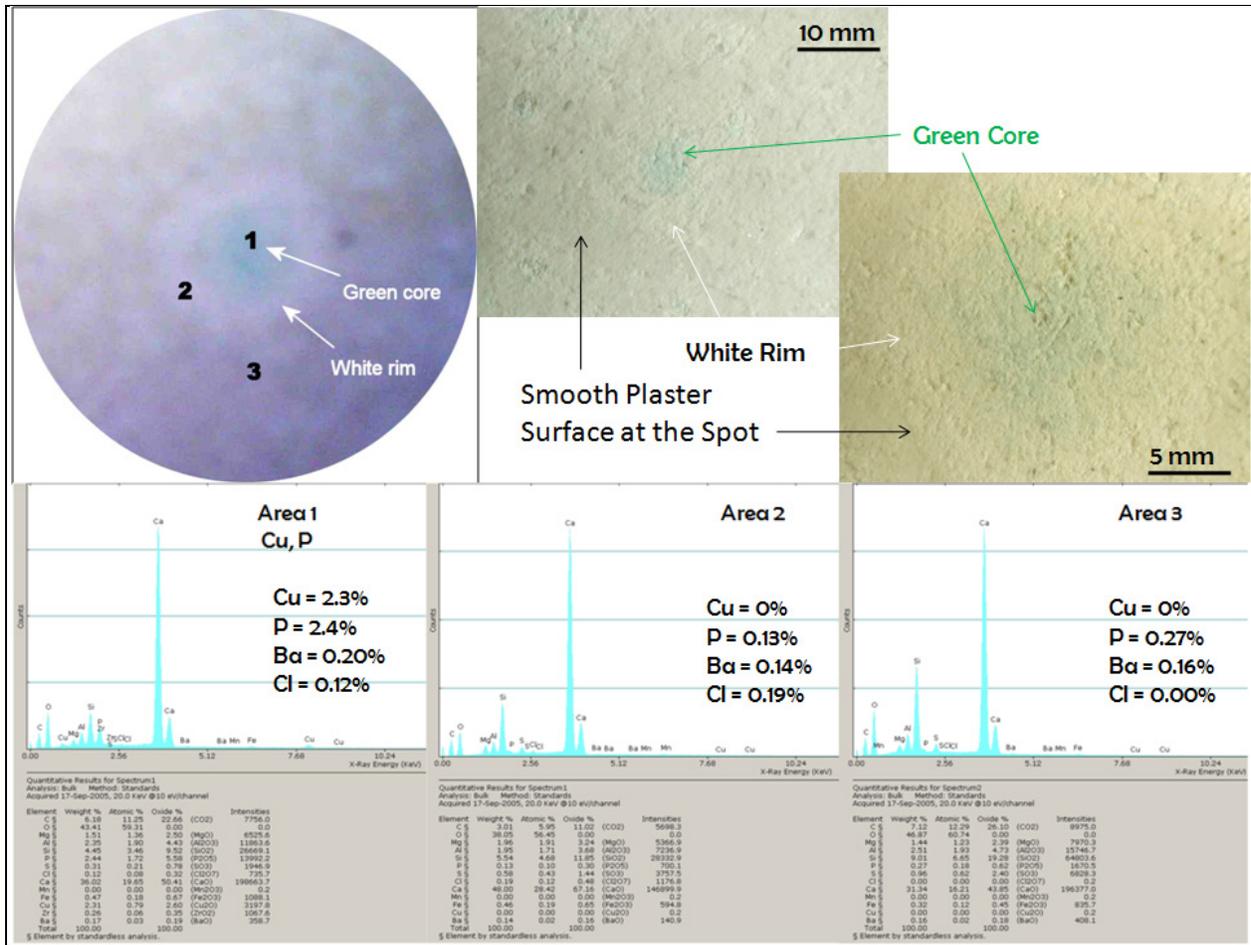


Figure 25 – The top left photo shows scanned image of a spot, where the green core, surrounded by a white rim are noticed. The two photomicrographs on the right show the spot at higher magnifications, where the green stain at the core is distinct. The lower three spectra are x-ray elemental analyses of the green core (marked as '1'), white rim (marked as '2'), and area away from the spot (marked as '3'), showing enrichment of copper, chlorine, and phosphorus at the spot. Copper stain at the spot is from copper algacides used in this pool, where the porous paste beneath the spot absorbed copper from the pool water.

Two common sources of copper in the green spots in field plaster are: (a) copper algacides, and (b) degradation of copper pipe or copper heat-exchangers of swimming pool heaters at the high chlorine and/or low pH (< 7.2) condition of pool water. The present one, as mentioned, was from copper algacides.

The following two figures show thin section and polished section photos, where cross sections of plaster were made over multiple surface spots (two spots in the left column photos and three spots in the right column photos in Figures 26 and 27), by using a continuous rim ultrathin diamond blade in a low speed saw. Prior to sectioning, individual spots were oven-dried at 60°C, vacuum impregnated with a fluorescent dye-mixed very low viscosity epoxy, and sectioned surfaces were further dried and impregnated with the same epoxy. The sections, thus prepared, showed three characteristic microstructural features: (a) microcracking in plaster beneath the spots, oriented perpendicular to the plaster surface, (b) carbonation of plaster at the surface region, down to a depth of 1/8 to 3/16 in. and greater depth along the microcracks (creating V-shaped carbonation front along the crack paths, indicating preexisting nature of the microcracks and not an artifact of sample preparation), and (c) a small zone of leached and porous paste, immediately beneath the spot, within the carbonated zone, where the paste being more porous than the adjacent areas, is highlighted by the fluorescent dye.

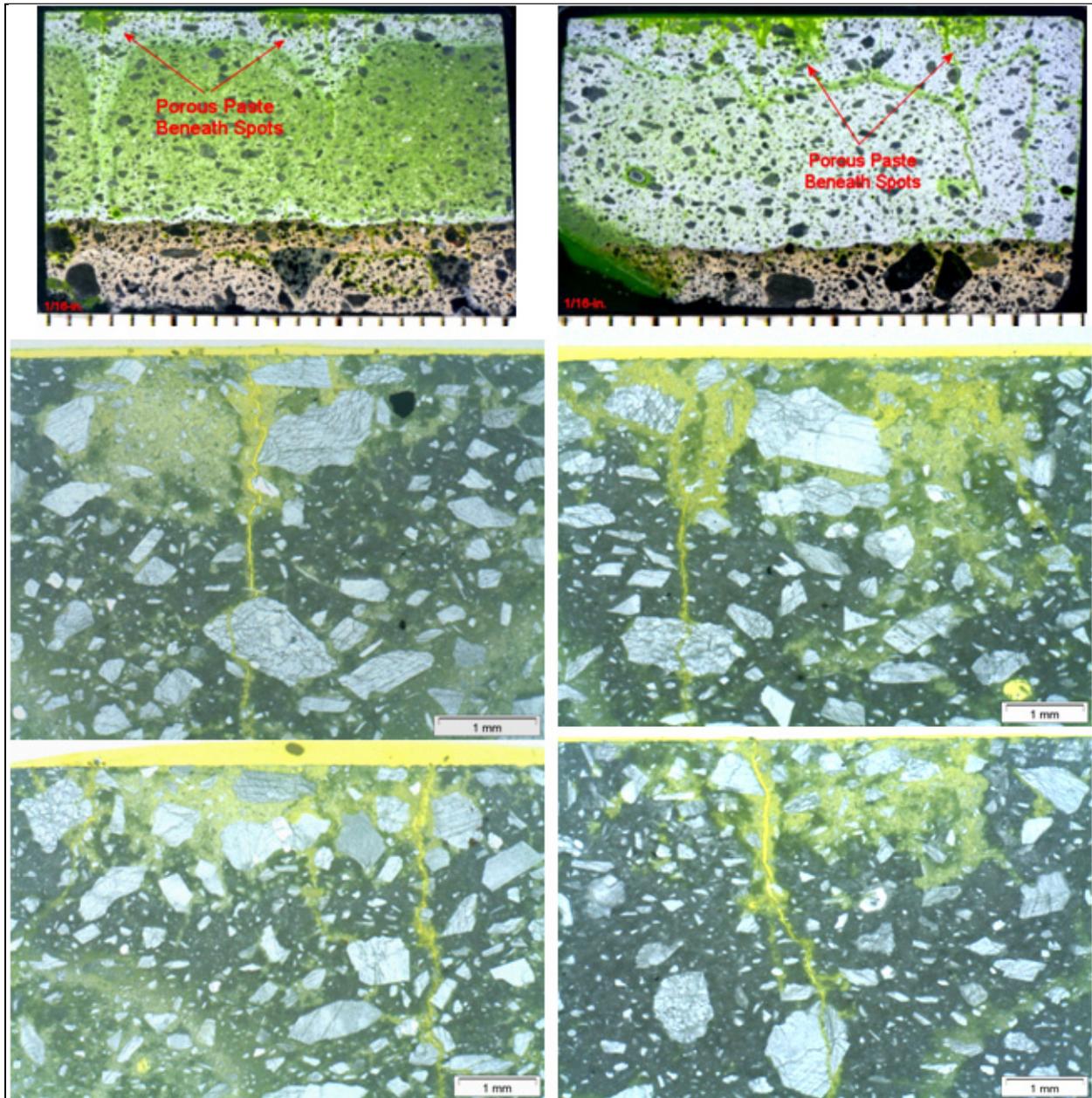


Figure 26 – Photomicrographs of polished fluorescent dye-mixed epoxy-impregnated thick sections (~100 microns thick) of plaster and concrete in the core, cross-sectioned through the spots, showing: (a) carbonation of plaster at the surface region, down to a depth of $\frac{1}{8}$ to $\frac{3}{16}$ in., where the carbonated paste at the surface being denser than the paste in the body showed a lower absorption of dyed epoxy than that in the body, a greater depth of carbonation along the vertical shrinkage microcracks than the areas in between the microcracks (creating V-shaped carbonation fronts along the paths of the microcracks), and (b) small zones of leached and porous paste at the surface, immediately beneath the spots, within the carbonated paste, which are highlighted by the fluorescent dye-mixed epoxy (marked with arrows).

The middle and bottom row photos are reflected-light photomicrographs of sections (by using an Olympus SZX12 stereo zoom microscope), where porous areas of paste around the microcracks and situated beneath the spots are readily highlighted by the yellow fluorescent dye-mixed epoxy.

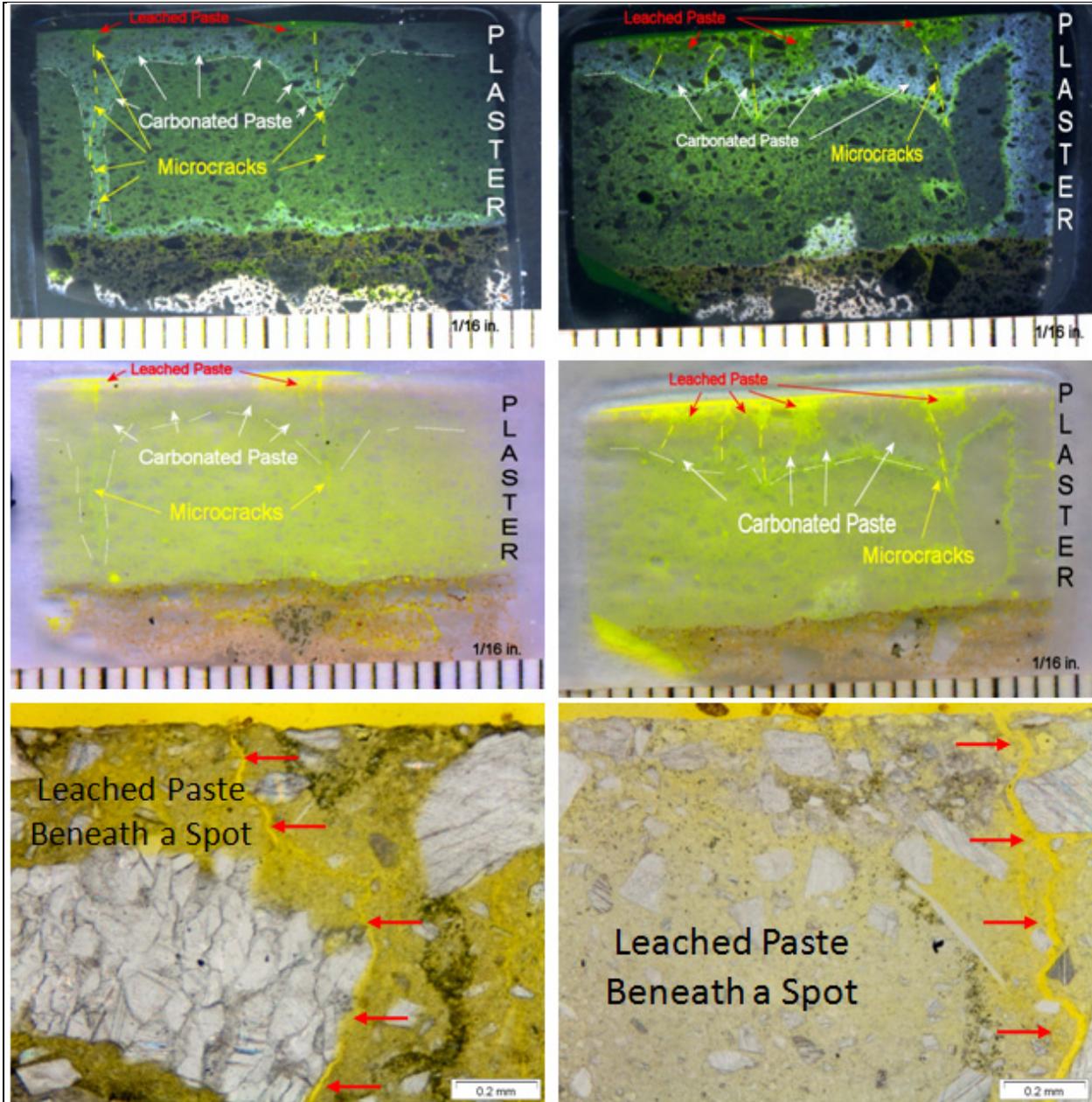


Figure 27 – Photomicrographs of fluorescent dye-mixed epoxy-impregnated thin sections (~ 30 microns thick) of plaster and concrete in the core, cross-sectioned through the spots (of the same samples shown in Figure 25 but after further grinding the sample thickness from ~ 100 to ~ 30 microns), showing: (a) carbonation of plaster at the surface region, down to a depth of $\frac{1}{8}$ to $\frac{3}{16}$ in., greater depth of carbonation along shrinkage microcracks (creating V-shaped carbonation front along the paths of the microcracks, and (b) small zones of leached paste immediately beneath the surface spots, where carbonated paste has been leached out relative to aggregates.

Sequence of events depicted by these photomicrographs in Figures 26 and 27 is – microcracking in plaster, followed by deep carbonation along the microcracks, which was followed by local leaching of carbonated paste beneath the spots in areas significantly smaller than the carbonated zone of paste.

The top and middle row photos are of the same thin sections, scanned on a flatbed scanner, by using a black and a white background, respectively. The lower row photos were taken by using a Nikon Labophot 2 POL petrographic microscope in plane polarized-light mode.

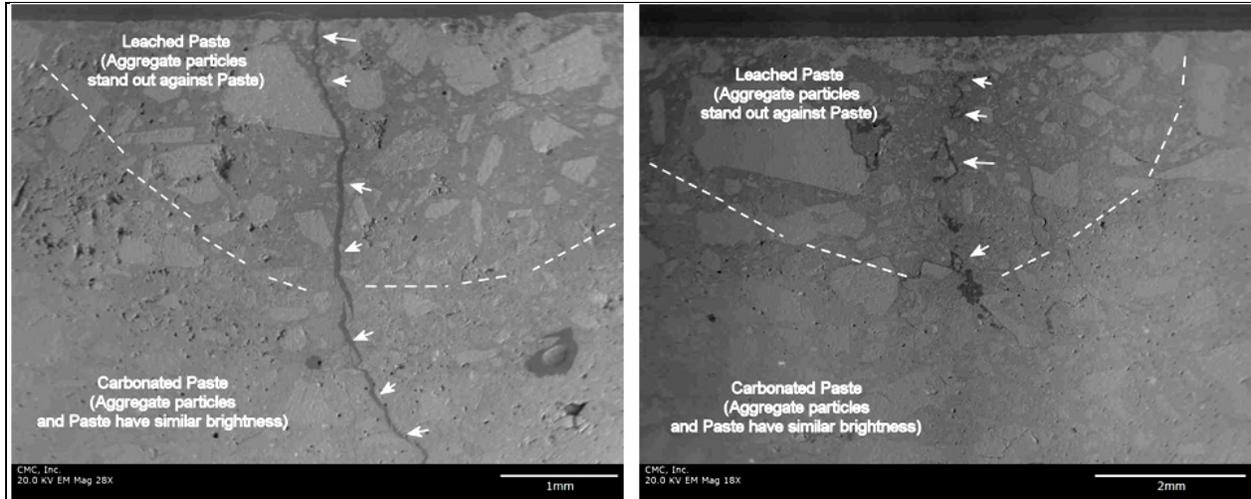


Figure 28 – Backscatter electron images of polished cross section of plaster (taken by using a CamScan Series II SEM) showing preferential leaching of paste relative to aggregates (areas within the dashed lines) beneath the surface spots causing proud exposure of aggregate against the paste, and, more or less non-differentiated aggregate and paste (carbonated) in areas away from the leached zones. Arrows mark shrinkage microcracks.

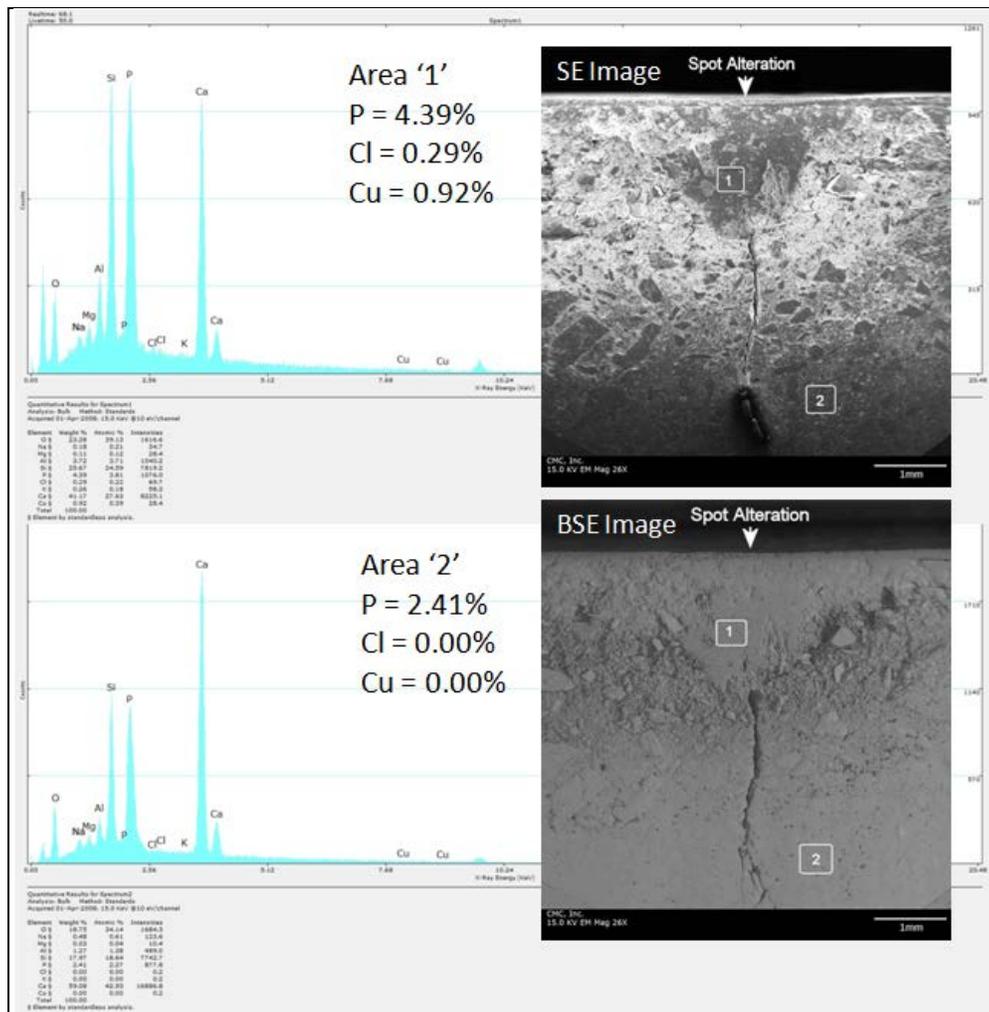


Figure 29 – X-ray elemental analyses of polished cross section of plaster showing P, Cu, and Cl enrichment in an area beneath the surface spot (marked as '1') and their depletion in an area away from the spot (marked as '2').

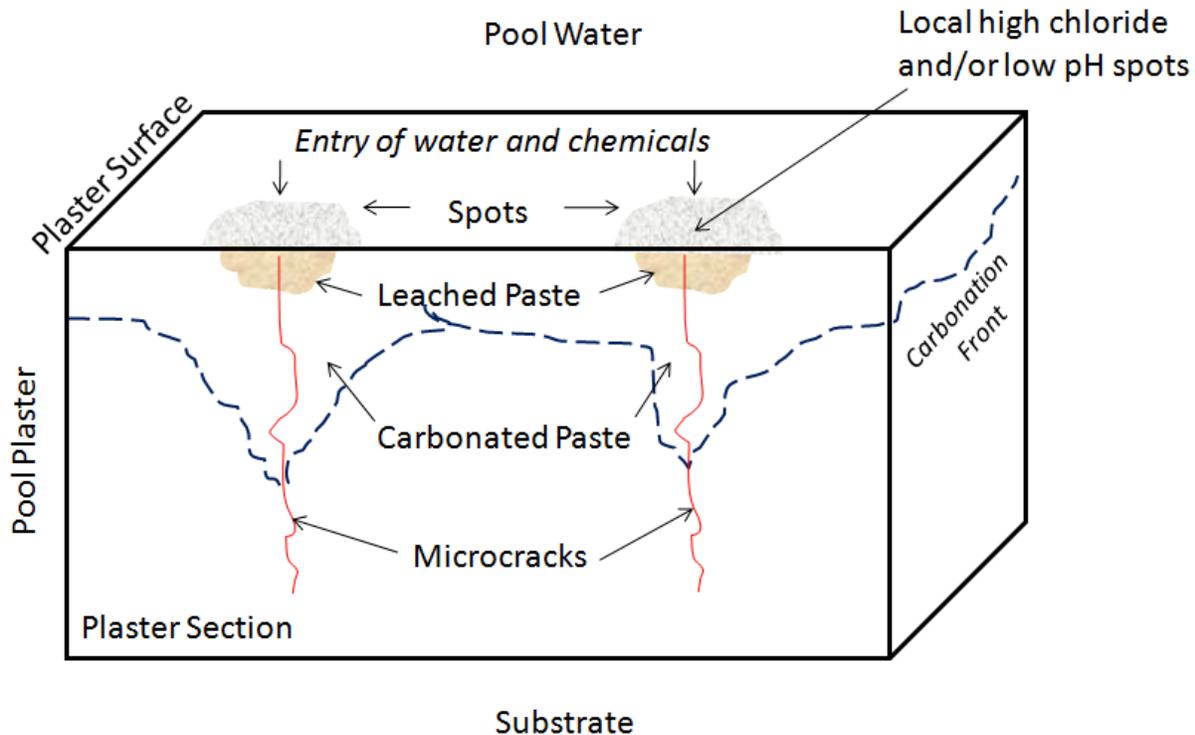


Figure 30 – A model of spot alteration based on the present case study, and recent researches of Rothstein et al. [11] and Arch Chemicals [12]. Preexisting microcracks on the plaster provided pathways for entry of pool water and chemicals. Certain chemicals (probably of high chloride and/or low pH chemistry) precipitated on the plaster surface, entered through the microcracks, and created a local high chloride and/or low pH environment at the surface have caused preferential leaching of cement hydration products, increased porosity of paste beneath the point of entry and, as a result, spot like discoloration of plaster at the sites of precipitation. The presence of microcracks helps entry of chemicals but is not necessary for spot alteration from excess chemicals in water.

Based on the present case study of occurrence of spot alteration at the locations of preexisting microcracks, as local leaching of paste beneath the spots, with no evidence of excess calcium chloride or improper finishing, and slightly elevated chloride levels in paste at the spots than elsewhere (Figure 29, similar to the findings of Rothstein et al. [11]), the author proposed a model (see Figure 30) where entry of water and chemicals having a high chloride/low pH chemistry (e.g., stabilizers) caused spot alteration at the loci of precipitation of chemicals on plaster surface at and around the microcracks. The presence of a preexisting microcrack, however, is not essential, since a local high chloride/low pH environment at the point of precipitation of such chemicals on the plaster surface can cause spot-like leaching of paste.

Author's own studies of spot alteration are consistent with previous findings of the absence of overall etching of plaster on or away from the spots and smoothness (on touch) of spots, evidence of localized paste leaching and porous paste at the spots, heavy metal enrichment from preferential staining at the spots, etc. The interpretation of findings by previous researchers, i.e., related to excess calcium chloride and improper plastering, however, is open to question, especially in lieu of the facts that:

- (a) Author's own observation of spot alteration in many cases, such as the one presented here, show normal calcium chloride dosage, and no evidence of finishing improprieties in the plaster, and,
- (b) Recent researches on the importance of excessive dosage of trichlor/CYA water treatment chemicals on spot alteration indicate influences of local high chloride/low pH environment causing spot-like leaching of surface paste, even in a balanced water pool, without necessarily causing an advanced etching.

The author did not detect any evidence of the occurrence of spot alteration around weakened aggregate-paste bond, or, it's nucleation around other areas of pre-existing weak areas on the plaster surface, but rather formation of spot-like leaching and associated localized porous paste (many around a preexisting microcracks acting as the entry path for the water and chemicals) on plasters that have been proportioned and finished properly. Spot alteration became common in the pool and spa industry more or less from the same time as the use of such high chlorine/low pH stabilizers¹⁰. In author's opinion, localized influences of such water-treatment chemicals (sanitizers, acidic stabilizers) in pool water (not necessarily aggressive) on selective leaching/pitting/staining of paste at the points of precipitation of chemicals on the plaster surface deserve a thorough and systematic research.

PLASTER SURFACE PITTING BY UNSOUND OR REACTIVE SAND

Apart from the above example of small surface pitting of plaster by spot-like leaching of paste, pitting on plaster surface can also occur by other ways. Sand used in plaster should be free of any impurities, non-reactive and in conformance to the guidelines of ASTM C 926 and ACI 524. Some unsound or reactive sand in plaster can react with plaster cement, in the presence of moisture to cause alkali-aggregate reaction and associated popout of plaster surface. Such reactions, however, seldom occur due to the neutral pH environment and low to moderate alkalinity of pool water in contact with the plaster. Small size of sand also reduces expansive stresses from such reactions, if it occurs, and limits the resultant popout size to less than 3 mm to a maximum 12 mm in the worst case. Other impurities in sand can cause small spots of staining or deterioration of plaster surface, e.g., certain clays, chert, zeolite, shale, opaline material, iron or copper metal contaminants in sand, etc.

FREEZING AND THAWING DAMAGE OF PLASTER

Damage due to cyclic freezing and thawing of plaster at critically saturated conditions is rare due to the underwater environment. Damage, however, can occur during plastering process by plastic freezing of plaster, or, prior to immersion in water. Portions of plaster not constantly underwater are susceptible to damage even during its service, due to the close proximity to a moist environment and intermittent drying and wetting phases [13] - those above-water portions of plaster in regions having anticipated sub-freezing temperatures in winter should have an added amount of air entrainment to increase resistance to freezing-related damage. Usually, a porous plaster is more resistant to freezing-related damage (due to its increased pore spaces to accommodate freezing-related stresses) than a dense, hard-troweled plaster.

PLASTER CARBONATION

Carbonation of pool plaster occurs by reactions of cement hydration products with atmospheric carbon dioxide, or dissolved carbonate and bicarbonate ions in pool water. Carbonation proceeds from exposed plaster surface inwards, and can invade the entire plaster thickness. Usually, plaster carbonation is not deleterious. However, pool water having a low carbonate alkalinity can convert calcium carbonate of carbonated plaster into water-soluble calcium bicarbonate, which can cause plaster surface deterioration. Carbonation of a freshly-placed plaster prior to water immersion can aggravate mottled, blotchy discoloration of the hard trowel-finished surface. Carbonation of a newly plastered surface can also cause shrinkage cracks to remain open due to the loss of calcium hydroxide component of cement hydration, which usually seals the cracks (the higher solid volume of calcite, the carbonation product, relative to calcium hydroxide, the cement hydration product, however, could play a beneficial role in crack sealing).

¹⁰ Randy Dukes, NPC, Personal Communication, April, 2008.

REMEDIES OF PLASTER DETERIORATION

The Technical Manual of National Plasterers Council provides various remedies of plaster deterioration as general guidelines [1]. A few remedial examples are:

- (a) Open plaster cracks are usually cleaned and filled (injected) with a cement paste, with or without sand and/or a polymer additive; extensive surface cracks may need to be resurfaced.
- (b) A soft or inferior plaster can gain strength by continued cement hydration underwater, otherwise, a surface hardener can be applied, which can reduce dusting, efflorescence, and strengthen the surface.
- (c) De-bonded plaster areas should be removed, exposed undercoat or substrate surface should be thoroughly cleaned of loose dirt or dust, and patched with a repair coat by a bonding agent, in a similar finishing/curing manner as the main plaster for intimate bond to the substrate and the remaining plaster.
- (d) Controlled acid washing, bleaching, sanding, grinding, and careful surface treatments with certain chemicals or stain removers are various methods of surface stain and scale removal. Acid washing, bleaching or chemical treatments can reduce large area discoloration.

Appropriate remedial actions are project-specific, which must be considered after consultation with the project personnel.

CONCLUSIONS

Various deteriorations of swimming pool plaster include cracking, softening, delamination, discoloration, staining, etching, scaling, surface pitting, carbonation, freezing-related damage, and spot alteration. Most of the pool plaster problems are associated with chemical or physical unsoundness in the substrate putting the plaster in tension, substrate settlement, improper plaster mix, disproportioning (e.g., excess CaCl_2 dosage), thickness, and finishing techniques, influences of pool water chemistry and water treatment chemicals on plaster, environments of plaster placement and service, and overall design. A systematic investigation of the plaster problem, including review of project background and thorough laboratory investigation of plaster samples can diagnose the cause(s) of problems, based on which appropriate repair strategies should be taken.

The paper presented fifteen different case studies of various such problems, summarized in Figure 31, diagnosed their causes, summarized as well in the Figure, and emphasized the importance of detailed laboratory investigation in determining reasons for these problems. Importance was given on the author's most frequently observed problems on plaster cracking, etching/scaling, delamination, discoloration, and spot alteration. Finally, a mechanism of spot alteration is proposed based on the observed chemical and microstructural properties of plaster in an interesting case study.

As seen in all cases, the basic issues of plaster problems are related to the quality and composition of plaster, the soundness and stability of substrate, the characteristics of pool water and its chemicals, pool maintenance, and the environment in which the plaster was placed and is in service (Figure 32). Improper plaster quality and/or mix proportions (e.g., excess sand, fines in sand, unsound or reactive sand, excess water, calcium chloride admixture, lime addition, etc.), and improper finishing practices (over-troweling, finishing with excess water, etc.) can lead to plaster cracking, softening, delamination, surface pitting, discoloration, and other problems. Imbalanced pool water can cause plaster scaling and etching. Heavy metals, minerals, contaminants in water can cause staining. An unstable substrate (e.g., expanding or settling) can induce plaster cracking. Plaster placement in a subfreezing temperature, or in a hot, dry, windy weather condition can cause cracking, softening, and delamination issues. Improper pool maintenance, e.g., excessive dosage of water treatment chemicals, or, inadequate brushing of leached lime from plaster and water at the early stage, etc. can cause plaster spotting or scaling. A good understating of all these systems, and their influences on plaster properties are, therefore, essential for prolonged durability and serviceability of swimming pool plaster.

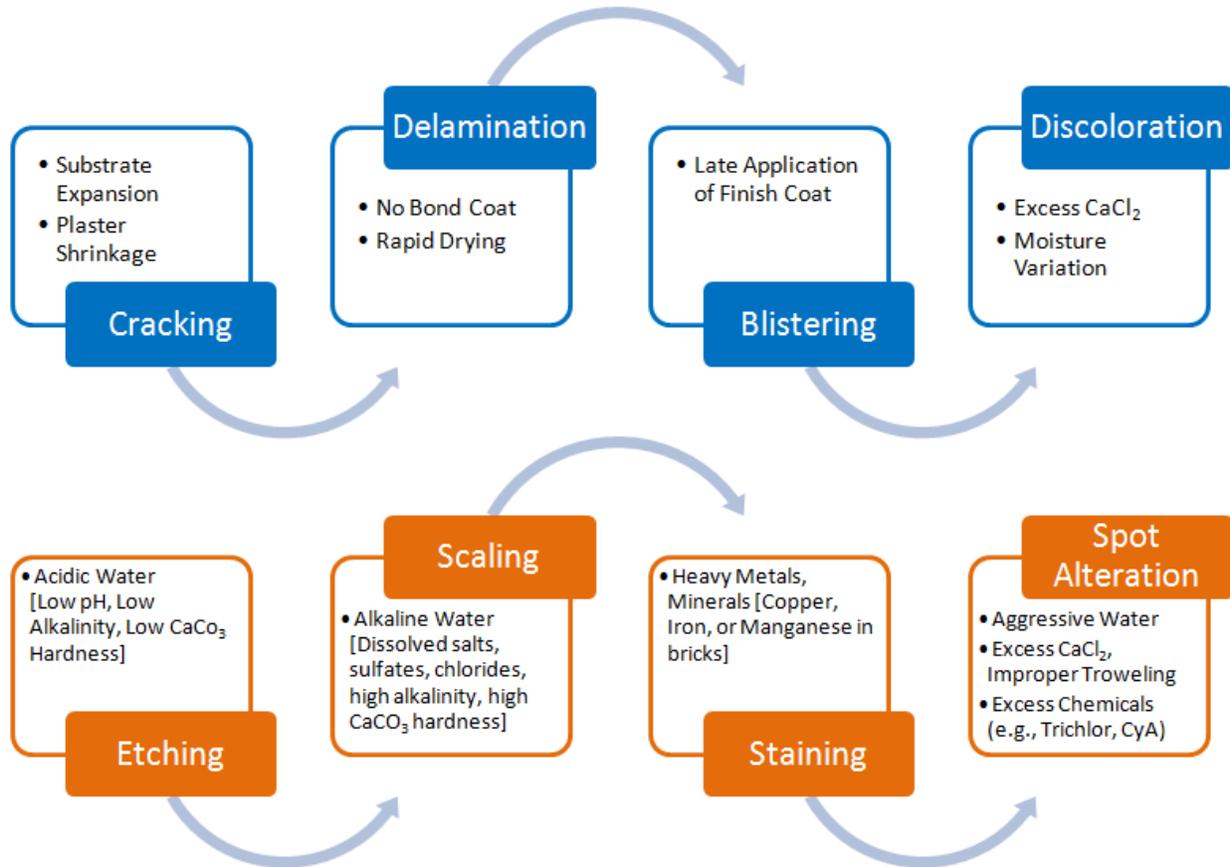


Figure 31 – A summary of case studies of plaster problems presented here and their causes (note the causes mentioned here are related to the present cases only, and may not be applicable to other cases of similar problems). Arched arrows do not indicate that one problem leads to the other.

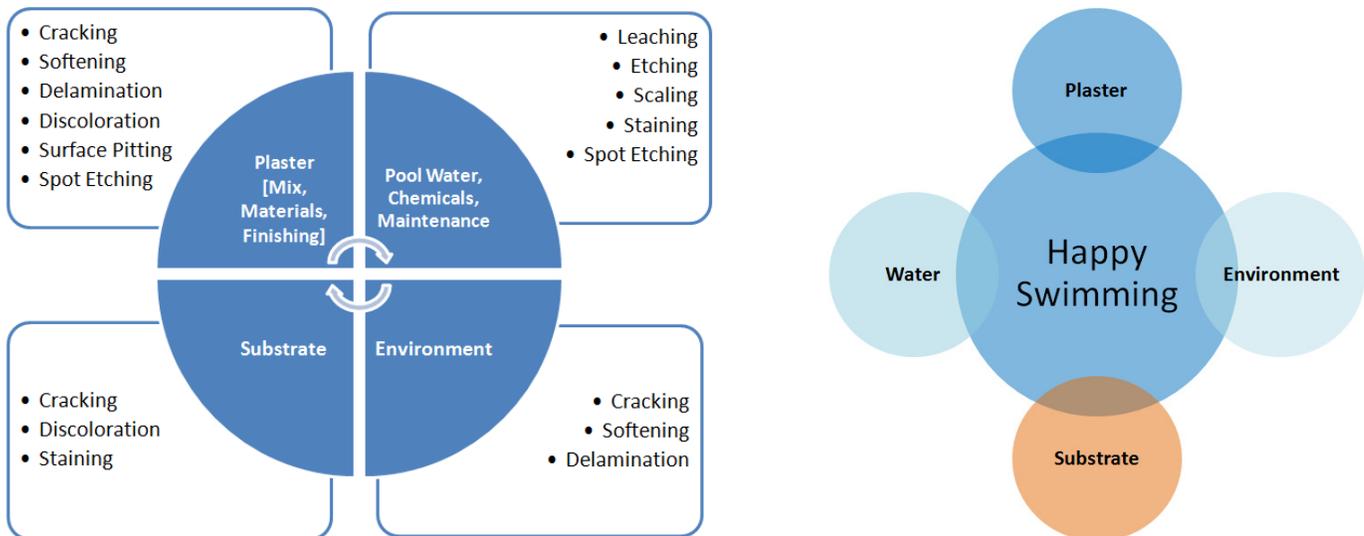


Figure 32 – Four major components responsible for most of the plaster problems (see the left photo). A basic understating of these four systems is, therefore, essential for prolonged durability and serviceability of plaster.

ACKNOWLEDGMENTS

Sincere thanks are due to all my pool and spa industry clients for providing many interesting case studies of pool plaster deterioration. The author is thankful to the National Plasterers Council for allowing use of materials from their Technical Manual. Terry Shaffer of Anthony and Sylvan Pools reviewed the manuscript, and has been a source of many enlightening discussions, and interesting case studies. Discussions with Mitch Brooks, Randy Dukes, and Greg Garrett of NPC, Inc. regarding spot alteration and their thoughts on various issues of plaster deterioration presented in the manuscript were very helpful. A detailed comment of the ACI 524 Plastering Committee Chairman, Jonathan E Dongell on an early version of the manuscript is highly acknowledged. Jennifer Lee Hall has prepared the reports of case studies and finalized the paper. Mitzi Casper has done meticulous petrographic sample preparation. My heartfelt thanks go to all, without whom this paper would not have been accomplished.

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