CONCRETE Information

Concrete Slab Surface Defects: Causes, Prevention, Repair

It is to the credit of concrete that so few complaints are received on the vast amount of construction put in place. While it is easy to determine the properties of the hardened concrete that will be suitable for the intended purpose, great care is required throughout the entire construction process to ensure that the hardened concrete actually has the desired properties. When a blemish appears on the surface of a concrete slab it will likely be one of these: blisters, cracking, crazing, curling, delamination, discoloration, dusting, efflorescence, low spots, popouts, scaling, or spalling. These deficiencies, caused by specific factors that are explained in the following paragraphs, can be minimized or prevented by adhering to proper construction methods.

Blisters

The appearance of blisters (Fig. 1) on the surface of a concrete slab during finishing operations is annoying. These bumps, of varying size, appear at a time when bubbles of entrapped air or water rising through the plastic concrete get trapped under an already sealed, airtight surface. Experienced concrete finishers attribute blistering to three principal causes:

1. An excess amount of entrapped air held within the concrete by a high percentage of material passing the 600 µm, 300 µm, and 150 µm (No. 30, 50, and 100) sieves, resulting in a sticky or tacky concrete that can become more easily sealed when floating or finishing it at any early age. Sticky mixes have a tendency to crust under drying winds while the remainder of the concrete remains plastic and the entrapped air inside rises to the surface. Usually, all that is needed to relieve this condition is to reduce the amount of sand in the mix. A reduction of 60 to 120 kg of sand per cubic meter of concrete (100 to 200 lb/yd^3) may be enough. (Replace the sand removed by adding a like amount of the smallest size coarse aggregate available.) The slightly harsher mix should release most of the entrapped air with normal vibration. On days when surface crusting occurs, slightly different finishing techniques may be needed, such as the use of wood floats to keep the surface open and flat troweling to avoid enfolding air into the surface under the blade action.

2. Insufficient vibration during compaction that does not adequately release entrapped air; or overuse of vibration that leaves the surface with excessive fines, inviting crusting and early finishing.

3. Finishing when the concrete is still spongy. Any tool used to compact or finish the surface will tend to force the entrapped air toward the surface. Blisters may not appear after the first finishing pass. However, as the work progresses (during the second or third pass), the front edge of the trowel blade is lifted to increase the surface density, and air under the surface skin is forced ahead of the blade until enough is concentrated (usually near a piece of large aggregate) to form blisters. Blisters, which will be full of water and air when picked, also can appear at any time and without apparent cause. Floating the concrete a second time helps to reduce blistering. Delayed troweling will depress the blisters even though it may not reestablish complete bond.

To avoid blisters, the following should be considered:

1. Do not use concrete with a high slump, excessively high air content, or excess fines.

2. Use appropriate cement contents in the range of 305 to 335 kg/m^3 (515 to 565 lb/yd^3).

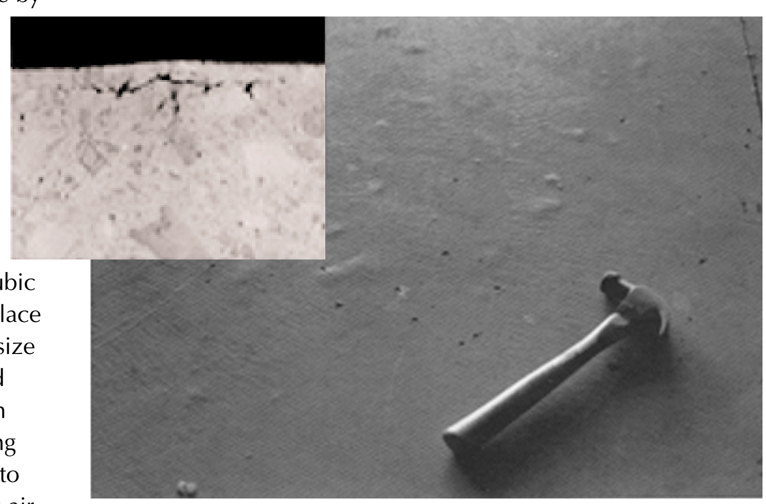

Figure 1. Blisters are surface bumps that may range in size from 5 mm to 100 mm (1/4 in. to 4 in.) in diameter with a depth of about 3 mm (1/8 in.). Inset photo cross section illustrates a void trapped under a blister. (Primary photo courtesy of National Ready Mixed Concrete Association.) (Inset, 49411; primary, A5272)

Figure 2. Plastic-shrinkage cracks caused by rapid loss of mix water while the concrete is still plastic. (1311)

3. Warm the subgrade before placing concrete on it during cold weather.
4. Avoid placing a slab directly on polyethylene film or other vapor barriers. Use a 100-mm (4-in.) layer of compactible, drainable fill (not sand). A "crusher run" material, usually graded from 38 mm to 50 mm (1-1/2 in. to 2 in.) down to rock dust, is suitable. Following compaction, the surface can be choked off with a fine-grade material to separate the vapor barrier from the concrete.
5. Avoid overworking the concrete, especially with vibrating screeds, jitterbugs, or bullfloats. Overworking causes aggregate to settle and bleed water and excess fines to rise. Properly vibrate to release entrapped air.
6. Do not attempt to seal (finish) the surface too soon. Use a wood bullfloat on non-air-entrained concrete to avoid early sealing. Magnesium or aluminum tools should be used on air-entrained concrete.
7. Use proper finishing techniques and proper timing during and between finishing operations. Flat floating and flat troweling are often recommended. Hand floating should be started when a person standing on a slab makes a 5-mm (1/4-in.) imprint or about a 3-mm (1/8-in.) imprint for machine floating. If moisture is deficient, a magnesium float should be used. Proper lighting is also very important during finishing.
8. Reduce evaporation over the slab by using a fog spray or slab cover.
9. Avoid using air contents over 3% for interior slabs.

Cracking

Unexpected cracking of concrete is a frequent cause of complaints. Cracking can be the result of one or a combination of factors, such as drying shrinkage, thermal contraction, restraint (external or internal) to shortening, subgrade settlement, and applied loads. Cracking can be significantly reduced when the causes are taken into account and preventative steps are utilized. For example, joints provided in the design and installed during construction force cracks to occur in places where they are inconspicuous.

Cracks that occur before hardening usually are the result of settlement within the concrete mass, or shrinkage of the surface (plastic-shrinkage cracks) caused by rapid loss of water while the concrete is still plastic (Fig. 2).

Settlement cracks may develop over embedded items, such as reinforcing steel, or adjacent to forms or hardened concrete as the concrete settles or subsides. Settlement cracking results from insufficient consolidation (vibration), high slumps (overly wet concrete), or a lack of adequate cover over embedded items.

Plastic-shrinkage cracks are relatively short cracks that may occur before final finishing on days when wind, a low humidity, and a high temperature occur. Surface moisture evaporates faster than it can be replaced by rising bleed water, causing the surface to shrink more than the interior concrete. As the interior concrete restrains shrinkage of the surface concrete, stresses develop that exceed the concrete's tensile strength, resulting in surface cracks. (Under certain combinations of conditions, warping or curling can result from these stresses, too. See Curling.) Plastic-shrinkage cracks are of varying lengths, spaced from a few centimeters (inches) up to 3 m (10 ft) apart, and often penetrate to middepth of a slab.

Cracks that occur after hardening usually are the result of drying shrinkage (Fig. 3), thermal contraction, or subgrade settlement. While drying, hardened concrete will shrink about 1.6 mm in 3 m (1/16 in. in 10 ft) of length. To accommodate this shrinkage and control the location of cracks, joints are placed at regular intervals. Experience has shown that contraction joints (induced cracks) should be spaced at about 3-m (10-ft) intervals in each direction in 100-mm-thick (4-in.) unreinforced concrete slabs on grade and at about 6-m (20-ft) intervals in 200-mm-thick (8-in.) slabs.

The major factor influencing the drying-shrinkage properties of concrete is the total water content of the concrete. As the water content increases, the amount of shrinkage increases proportionally. Large increases in the sand content and significant reductions in the size of the coarse aggregate increase shrinkage because total water is increased and because smaller size coarse aggregates provide less internal restraint to shrinkage. Use of high-shrinkage aggregates and calcium chloride admixtures also increases shrinkage. Within the range of practical concrete mixes—280 to 445 kg/m^3 cement content (470 to 750 lb/yd^3, or “5- to 8-bag” mixes)—increases in cement content have little to no effect on shrinkage as long as the water content is not increased significantly.

Silica fume can make highly cohesive, sticky concrete, with little bleeding capacity. With little or no bleed water on the surface, silica fume concrete is prone to plastic shrinkage cracking on hot, windy days. Fogging the air above the concrete and erecting windshades lessen the risk of plastic-shrinkage cracking.

Concrete has a coefficient of thermal expansion and contraction of about 10 x 10^{-6} per °C (5.5 x 10^{-6} per °F). Concrete placed during hot midday temperatures will contract as it cools during the night. A 22°C (40°F) drop in temperature between day and night—not uncommon in some areas—would cause about 0.7 mm (0.03 in.) of contraction in a 3-m (10-ft) length of concrete, sufficient to cause cracking if the concrete is restrained. Thermal expansion can also cause cracking.

Insufficiently compacted subgrades and soils susceptible to frost heave or swelling can produce cracks in slabs. Overloading of concrete slabs also results in flexural crack formation and possible failure.

Cracking in concrete can be reduced significantly or eliminated by observing the following practices:

1. Use proper subgrade preparation, including uniform support and proper subbase material at adequate moisture content.
2. Minimize the mix water content by maximizing the size and amount of coarse aggregate and use low-shrinkage aggregate.
3. Use the lowest amount of mix water required for workability; do not permit overly wet consistencies.
4. Avoid calcium chloride admixtures.
5. Prevent rapid loss of surface moisture while the concrete is still plastic through use of spray-applied finishing aids or plastic sheets to avoid plastic-shrinkage cracks.
6. Provide contraction joints at reasonable intervals, 30 times the slab thickness.
7. Provide isolation joints to prevent restraint from adjoining elements of a structure.
8. Prevent extreme changes in temperature.
9. To minimize cracking on top of vapor barriers, use a 100-mm-thick (4-in.) layer of slightly damp, compactible, drainable fill choked off with fine-grade material. If concrete must be placed directly on polyethylene sheet or other vapor barriers, use a mix with a low water content.

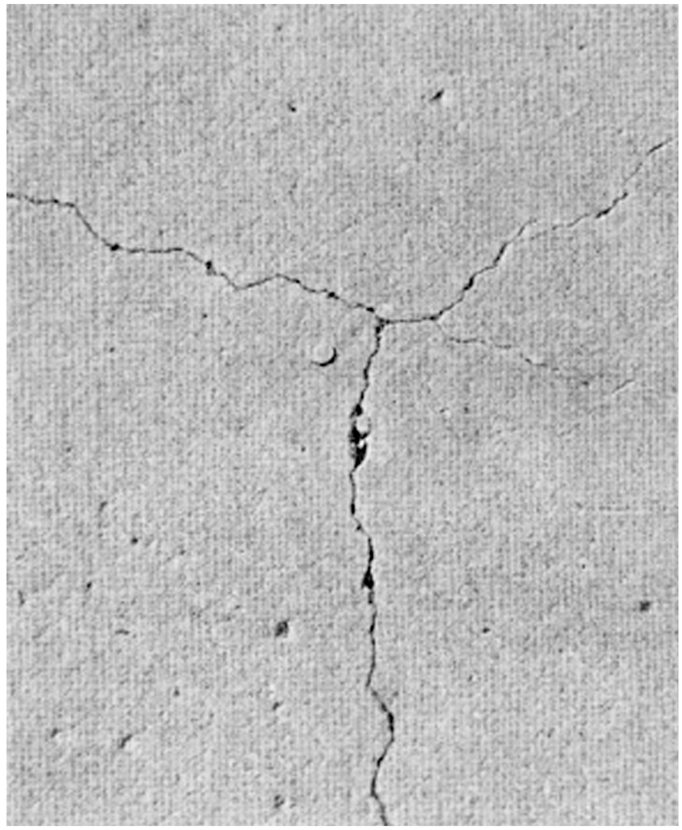

Figure 3. Drying-shrinkage cracks like these often result from improper joint spacing. (A5271)

10. Properly place, consolidate, finish, and cure the concrete.
11. Avoid using excessive amounts of cementitious materials.
12. Consider using a shrinkage-reducing admixture to reduce drying shrinkage, which may reduce shrinkage cracking.
13. Consider using synthetic fibers to help control plastic shrinkage cracks.

Refer to the section on curling for more recommendations on how to reduce shrinkage.

Cracks can also be caused by freezing and thawing of saturated concrete, alkali-aggregate reactivity, sulfate attack, or corrosion of reinforcing steel. However, cracks from these sources may not appear for years. Proper mix design and selection of suitable concrete materials can significantly reduce or eliminate the formation of cracks and deterioration related to freezing and thawing, alkali-aggregate reactivity, sulfate attack, or steel corrosion. For more information, refer to *Design and Control of Concrete Mixtures*, EB001, and *Diagnosis and Control of Alkali-Aggregate Reactions in Concrete*, IS413.

Crazing

Crazing, a network pattern of fine cracks that do not penetrate much below the surface, is caused by minor surface shrinkage

Figure 4. Crazing is a network of fine surface cracks. (4099)

(Fig. 4). Crazing cracks are very fine and barely visible except when the concrete is drying after the surface has been wet. The cracks encompass small concrete areas less than 50 mm (2 in.) in dimension, forming a chicken-wire pattern. The term "map cracking" is often used to refer to cracks that are similar to crazing cracks only more visible and surrounding larger areas of concrete. Although crazing cracks may be unsightly and can collect dirt, crazing is not structurally serious and does not ordinarily indicate the start of future deterioration.

When concrete is just beginning to gain strength, the climatic conditions, particularly the relative humidity during the drying period in a wetting and drying cycle, are an important cause of crazing. Low humidity, high air temperature, hot sun, or drying wind, either separately or in any combination, can cause rapid surface drying that encourages crazing. A surface into which dry cement has been cast to hasten drying and finishing will be more subject to crazing. The conditions that contribute to dusting, as described below, also will increase the tendency to craze.

To prevent crazing, curing procedures should begin early, within minutes after final finishing when weather conditions warrant. When the temperature is high and the sun is out, some method of curing with water should be used, since this will stop rapid drying and lower the surface temperature. The concrete should be protected against rapid changes in temperature and moisture wherever feasible.

Curling

Curling is the distortion (rising up) of a slab's corners and edges due to differences in moisture content or temperature between the top and bottom of a slab. The top dries out or cools and shrinks more than the wetter or warmer bottom. If the curled section of a slab is loaded beyond the flexural strength of the concrete, cracks may develop to relieve the stress. Curling can be reduced by:

1. Using a low-shrinkage concrete mix.
2. Using proper control-joint spacing (see Cracking).
3. Creating uniform moisture content and temperature of the slab from top to bottom.
4. Using large amounts of reinforcing steel 50 mm (2 in.) down from the surface.
5. Using thickened slab edges.
6. Using vacuum dewatering, shrinkage-compensating concrete, or post-tensioning.

Shrinkage in a mix can be reduced by (1) using a low water content, (2) reducing sand content and maximizing the coarse aggregate content, (3) using low-shrinkage and well-graded aggregates of the largest practical size, (4) avoiding calcium chloride or other admixtures that may increase shrinkage, and (5) reducing the temperature of the plastic (fresh) concrete.

Another way to reduce shrinkage of concrete is to use a shrinkage-reducing admixture (typical dosage, 2%). The reduction in shrinkage (%) increases with an increase in curing time and with the use of low water-cementitious materials ratios. Because shrinkage-reducing admixtures reduce drying shrinkage, they may lessen the tendency for curling in slabs on grade.

The moisture content can be stabilized by (1) prompt and proper curing—curing compounds may help reduce moisture differentials by slowing down the rate of moisture loss over a long period of time, (2) applying moisture-insensitive sealers or coatings to slab surfaces—do not use vapor-impermeable sealers on slabs exposed to freezing in the presence of moisture to avoid delamination (use breathable formulations) and (3) where allowable use a well-drained, coarse granular fill instead of vapor barriers. Fill and subgrade beneath the slab must not be allowed to become and remain saturated. If a vapor barrier is required, place about 100 mm (4 in.) of compactible, drainable fill (not sand) over the vapor barrier. This material can be choked off with a fine-grade material to reduce friction between the base material and the slab, and should be damp enough to be compacted, but dry enough to act as a blotter.

Temperature extremes can be reduced by using insulation over or under the slab or by controlling the ambient air temperature.

The degree of curling is often significantly reduced with time as the slab dries and achieves a more uniform moisture content and temperature. If moisture-related curling persists, one possible remedy is to pond the slab until it is level again and cut additional control joints where the slab has curled. The success of this remedy is variable, often depending upon the extent and cause of the curling. This method creates additional joints, a consideration for slab maintenance.

Grinding also may restore serviceability. Portland cement grout can be injected to fill voids and restore bearing in uplifted portions of a slab; after the grout hardens, the surface can be ground down to its original plane with power grinding equipment.

Delamination

Delaminations are similar to blisters in that delaminated areas of surface mortar result from bleed water and bleed air being trapped below the prematurely closed (densified) mortar surface. The primary cause is finishing the surface before bleeding has occurred. Delaminations are also more likely to occur when factors that extend the bleeding time of concrete (e.g. cold substrate) are combined with factors that accelerate surface setting (e.g. high ambient air temperature).

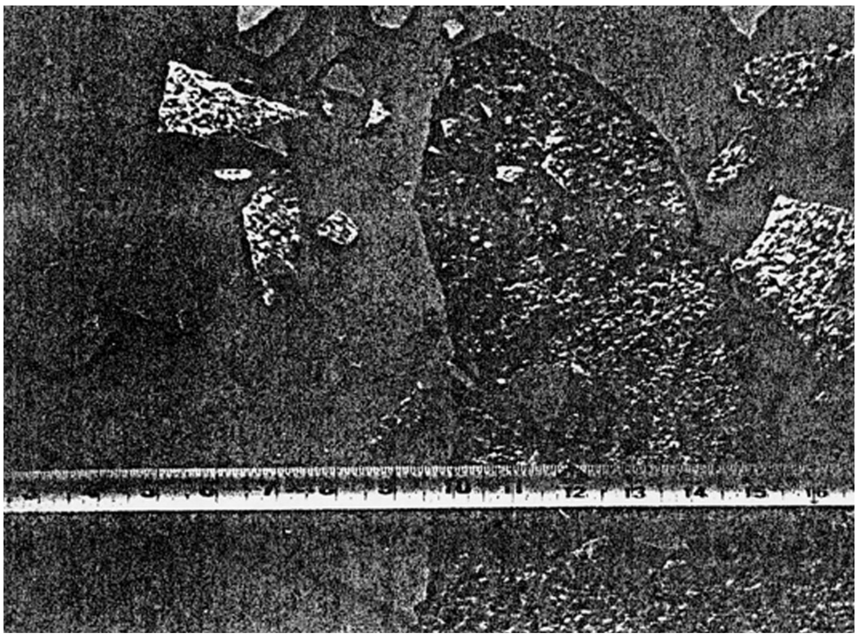

Figure 5. This delamination is the result of sealing the surface before bleeding has occurred. (67196)

It is necessary to wait for a period of time after placing the concrete to allow air and water to escape from the concrete. The waiting period varies with the concrete mixture, mixing and placing procedures, and weather conditions. Delaminations are very difficult to detect during finishing and become apparent after the concrete surface has dried and the delaminated area is crushed under traffic. The delaminated mortar thickness ranges from about 3 mm to 5 mm (1/8 in. to 1/4 in.). To avoid conditions that lead to delaminations, see the recommendations under the section on blisters.

Delaminations also may be the result of disruptive stresses from chloride-induced corrosion of steel reinforcement or of poorly bonded areas in two-course construction. The resulting delaminations are deeper than those caused by trapped air or bleed water and are often called spalls (see Spalls).

A delaminated area that has separated from the underlying concrete can leave a hole in the surface and resembles spalling (see Fig. 5). A delamination survey can be conducted by sounding—dragging a chain across the surface or tapping with a hammer and listening for hollow sounds. A hollow sound indicates delaminated areas, and a ringing sound indicates intact areas. This test is described in ASTM D 4580, *Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding*. Nonstandard methods for detecting delaminated areas are acoustic impact, infrared thermography, and ground-penetrating radar. Delaminations can be repaired by patching or, if widespread, by grinding and overlaying with a new surface. Epoxy injection may also be beneficial in some applications.

Discoloration

Surface discoloration of concrete flatwork can appear as gross color changes in large areas of concrete, spotted or mottled light or dark blotches on the surface, or early light patches of efflorescence (see section below).

Laboratory studies to determine the effects of various concreting procedures and concrete materials show that no single factor is responsible for all discoloration. Factors found to influence discoloration are calcium chloride admixtures, cement alkalies, hard-troweled surfaces, inadequate or inappropriate curing, a wet substrate, variation of the water-cement ratio at the surface, and changes in the concrete mix. Discoloration from these causes appears very soon after placing the concrete.

Discoloration at later ages may be the result of atmospheric or organic staining—simply stated, the concrete is dirty. This type of discoloration is usually removed by power washing with pressurized water and, possibly, chemical cleaners.

The use of calcium chloride in concrete may discolor the surface (Fig. 6). Calcium chloride accelerates the hydration process but has a retarding effect on the hydration of the ferrite compound in portland cement. The ferrite phase normally becomes lighter with hydration; however, in the presence of calcium chloride the retarded, unhydrated ferrite phase remains dark.

Extreme discoloration can result from attempts to hard-trowel the surface after it has become too stiff to trowel properly. Vigorously troweling a surface to progressively compact it can reach the point where the water-cement ratio is drastically decreased in localized areas. This dense, low-water-cement-ratio concrete in the hard-troweled area is almost always darker than the adjacent concrete.

Waterproof paper and plastic sheets used to moist-cure concrete containing calcium chloride have been known to give a mottled appearance to flat surfaces due to the difficulty in placing and keeping a cover in complete contact with the surface over the entire area. The places that are in contact will be lighter in color than those that are not.

Concrete materials and proportions affect concrete color. Individual cements may differ in color. Thus, substituting one cement for

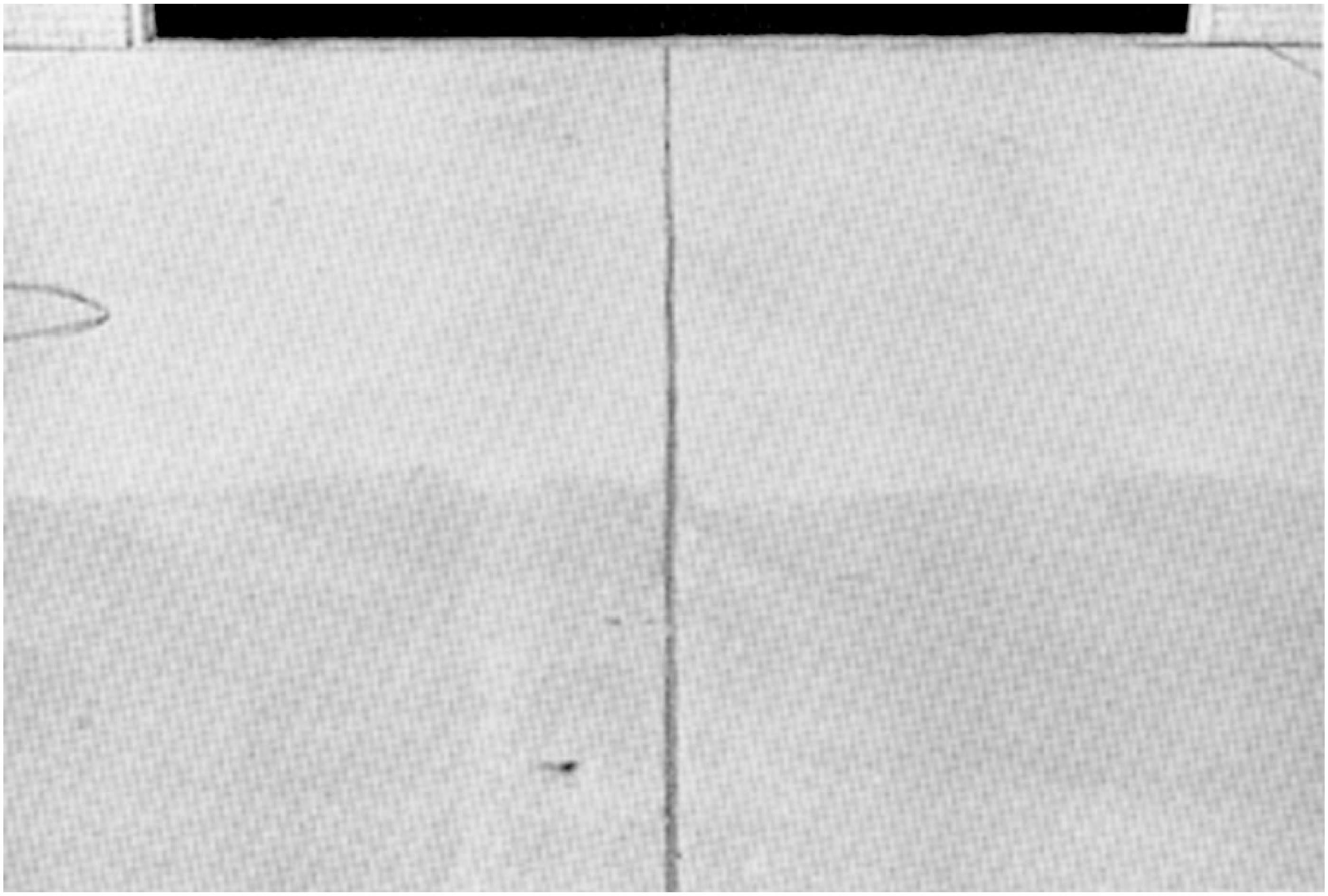

Figure 6. Driveway discoloration due to the use of a calcium chloride admixture in the concrete at the bottom but not the top of the photo. This illustrates just one of several types of discoloration. (14019)

another may change the color of concrete. Concretes containing significant amounts of mineral admixtures—fly ash, silica fume, metakaolin, or slag, for example—may differ in color from those containing no mineral admixture. The color of the sand has an effect on the color of the concrete. High-strength concrete with a low water-cement ratio is darker in color than low-strength concrete with a high water-cement ratio.

The discoloration of concrete can be avoided or minimized by (1) avoiding the use of calcium chloride admixtures, (2) using consistent concrete ingredients, uniformly proportioned from batch to batch, and (3) using proper and timely placing, finishing, and curing practices. Concreting practices should not be allowed to vary, as any disruption or change in the concrete mixture, formwork, finishing, or curing can result in significant and sometimes permanent discoloration.

To eradicate discoloration, the first (and usually effective) remedy is an immediate, thorough flushing with water. Permit the slab to dry, then repeat the flushing and drying until the discoloration disappears. If possible, use hot water. Acid washing using concentrations of weaker acids such as 3% acetic acid (vinegar) or 3% phosphoric acid will lessen carbonation and mottling discoloration. Treating a dry slab with 10% solution of caustic soda (sodium hydroxide) gives some success in blending light spots into a darker background. Harsh acids should not be used, as they can expose the aggregate.

One of the best methods to remove most discoloration, when other remedies have failed, is to treat a surface with a 20% to 30% water solution of diammonium citrate. This chemical is expensive to buy in small quantities, so consider it as a last resort. These and other treatments and recommendations to prevent and eradicate discoloration are contained in *Surface Discoloration of Concrete Flatwork*, RX203; “Discoloration of Concrete—Causes and Remedies,” *Concrete Technology Today*, PL861; “Pinto Concrete—Is There a Cure?” *Concrete Technology Today*, PL961; and “Reader Response: Discoloration,” *Concrete Technology Today*, PL962.

Staining discolored concrete with a chemical stain is another way to make color variations less noticeable. Usually, darker colors hide color variations more effectively. Chemical stains can be used on interior or exterior concrete.

A rare discoloration ranging in color from buff to red/orange has been reported in Wisconsin, Illinois, Louisiana, and other states. This type of discoloration is more likely to occur during periods of high relative humidity and high ambient temperature. This staining occurs more often with certain types and amounts of wet-curing. Fly ash aggravates the staining by intensifying the color.

This staining is probably caused by differences in curing and degree of hydration of the surface cementitious materials under high humidity and high ambient temperature conditions. In particular, additional hydration of the ferrite compounds in cementitious materials leads to more reduced iron being available to oxidize and discolor the concrete. Research has found that the staining occurs under a certain set of conditions, which includes the availability of water and oxygen. Rapid drying of the concrete results in insufficient moisture to produce staining, while continuous immersion does not allow access of air. In both cases, discoloration does not occur. Therefore, it is recommended that the concrete be kept fully wet for the required curing period, then allowed to dry as rapidly as possible thereafter. For instance, wet burlap with a plastic sheet covering should be removed in the morning of a hot day rather than in the evening or before rain is expected.

This type of staining is difficult to remove. Commercial sodium bisulfate cleaners are somewhat successful in removing the stain; however, the difference between cleaned and stained areas decreases over several weeks. The following chemicals are largely ineffective at removing these buff to red/orange stains: hydrochloric acid (2%), hydrogen peroxide (3%), bleach, phosphoric acid (10%), diammonium citrate (0.2M), and oxalic acid (3%). (Miller, Powers, and Taylor 1999, and Taylor, Detwiler, and Tang 2000)

Dusting

Dusting—the development of a fine, powdery material that easily rubs off the surface of hardened concrete—can occur either indoors or outdoors, but is more likely to be a problem when it occurs indoors (Fig. 7). Dusting is the result of a thin, weak layer, called laitance, composed of water, cement, and fine particles.

Fresh concrete is a fairly cohesive mass, with the aggregates, cement, and water uniformly distributed throughout. A certain amount of time must elapse before the cement and water react sufficiently to develop hardened concrete. During this period, the cement and aggregate particles are partly suspended in the water. Because the cement and aggregates are heavier than water, they tend to sink. As they move downward, the displaced water moves upward and appears at the surface as bleed water, resulting in more water near and at the surface than in the lower portion of the concrete. Thus, the laitance—the weakest, most permeable, and least wear-resistant concrete—is at the top surface, exactly where the strongest, most impermeable, and most wear-resistant concrete is needed.

Floating and troweling concrete with bleed water on it mixes the excess water back into the surface, further weakening the concrete's strength and wear resistance and giving rise to dusting. Dusting may also be caused by (1) water applied during finishing, (2) exposure to rainfall during finishing, (3) spreading dry cement over the surface to accelerate finishing, (4) a low cement content, (5) too wet a mix, (6) lack of proper curing (especially allowing

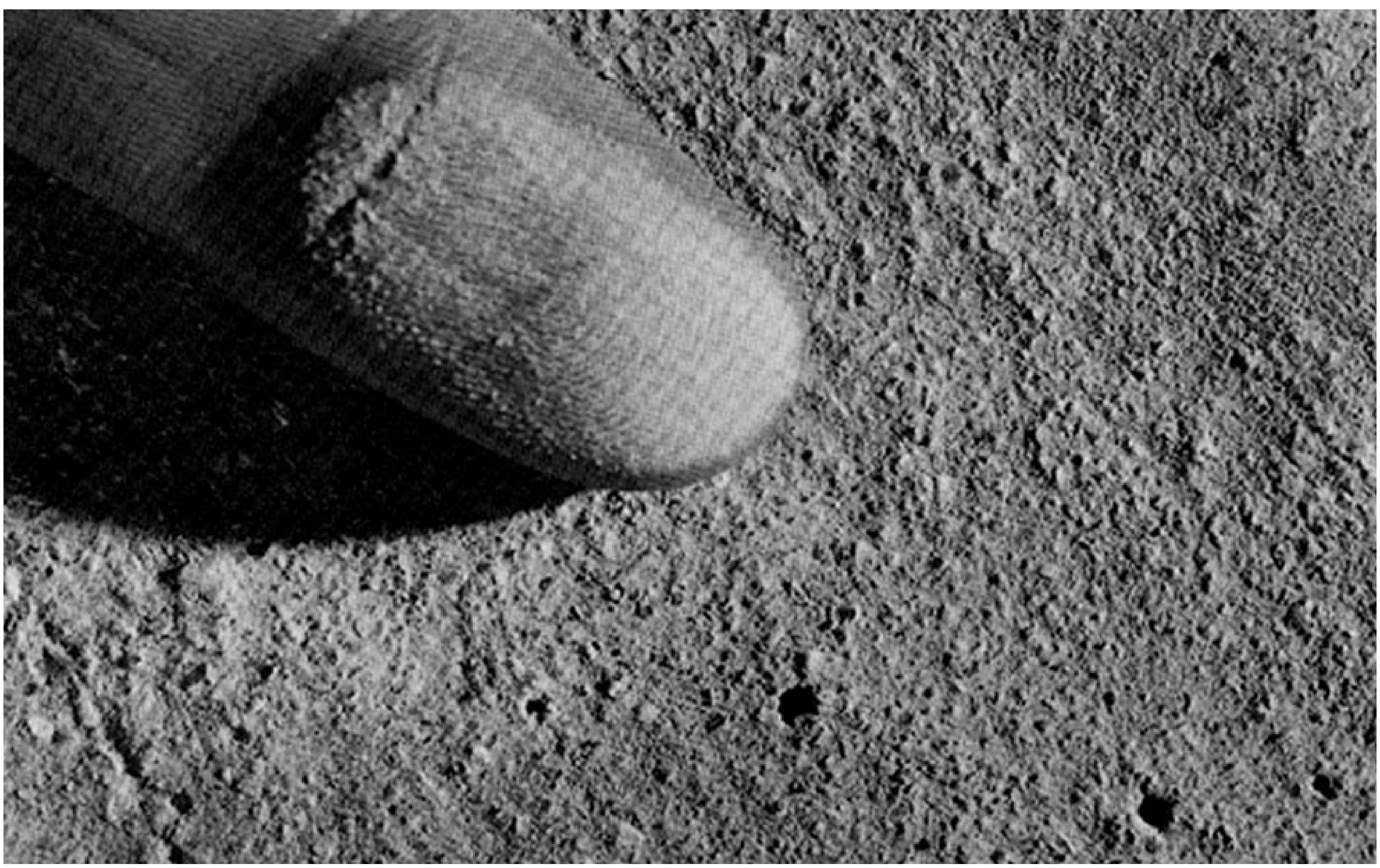

Figure 7. Dusting is evident by the fine powder that can be easily rubbed off the surface. (1297)

rapid drying of the surface), (7) carbonation during winter concreting (caused by unvented heaters), (8) freezing of the surface, and (9) dirty aggregate.

Heated enclosures are commonly used for protecting concrete when air temperatures are near or below freezing. The enclosures frequently are heated by oil- or propane-fired blowers or coke-burning salamanders. As these heaters produce a dry heat, care must be taken to prevent rapid drying of the concrete surface, especially near the heater. The burning of fuel also produces carbon dioxide that will combine with the calcium hydroxide in fresh concrete to form a weak layer of calcium carbonate on the surface. When this occurs, the floor surface will dust under traffic. For this reason, carbon dioxide-producing heaters should not be used while placing and finishing concrete and during the first 24 to 36 hours of the curing period unless properly vented to outside the heated enclosure.

One way to correct a dusting surface is to grind off the thin layer of laitance to expose the solid concrete underneath. Another method is to apply a surface hardener. This treatment will not convert a basically bad concrete slab into a good one; it will, however, improve wearability and reduce dusting of the surface.

The major ingredient in many floor-surface hardeners is sodium silicate (water glass) or a metallic silicofluoride (magnesium and zinc fluosilicates are widely used). The treatment is usually applied in two or three coats, letting the surface dry between each application. More information is available in *Concrete Floors on Ground*, EB075.

Efflorescence

Efflorescence can be considered a type of discoloration. It is a deposit, usually white in color, that occasionally develops on the surface of concrete, often just after a structure is completed. Although unattractive, efflorescence is usually harmless. In rare cases, excessive efflorescence deposits can occur within the surface pores of the material, causing expansion that may disrupt the surface.

Efflorescence is caused by a combination of circumstances: soluble salts in the material, moisture to dissolve these salts, and evaporation or hydrostatic pressure that moves the solution toward the surface. Water in moist, hardened concrete dissolves soluble salts. This salt-water solution migrates to the surface by evaporation or hydraulic pressure where the water evaporates, leaving a salt deposit at the surface. Efflorescence is particularly affected by temperature, humidity, and wind. In the summer, even after long rainy periods, moisture evaporates so quickly that comparatively small amounts of salt are brought to the surface. Usually efflorescence is more common in the winter when a slower rate of evaporation allows migration of salts to the surface. If any of the conditions that cause efflorescence—water, evaporation, or salts—are not present, efflorescence will not occur.

All concrete materials are susceptible to efflorescence. Even small amounts of water soluble salts (a few tenths of a percent) are sufficient to cause efflorescence when leached out and concentrated at the surface. In most cases, these salts come from beneath the surface, but chemicals in the materials can react with chemicals in the atmosphere to form efflorescence. For example, hydration of cement in concrete produces soluble calcium hydroxide, which can migrate to the surface and combine with carbon dioxide in the air to form a white calcium carbonate deposit.

All concrete ingredients should be considered for soluble-salt content. Common efflorescence-producing salts are carbonates of calcium, potassium, and sodium; sulfates of sodium, potassium, magnesium, calcium, and iron; and bicarbonate of sodium or silicate of sodium. To reduce or eliminate soluble salts:

1. Never use unwashed sand. Use sand that meets the requirements of ASTM C 33 or CSA A23.1 for concrete.
2. Use clean mixing water free from harmful amounts of acids, alkalies, organic material, minerals, and salts. Drinking water is usually acceptable. Do not use seawater.

Low absorption of moisture is the best assurance against efflorescence. Cast-in-place concrete will have maximum watertightness when made with properly graded aggregates, an adequate cement content, a low water-cement ratio, and thorough curing.

When there is efflorescence, the source of moisture should be determined and corrective measures taken to keep water out of the structure. Chloride salts are highly soluble in water, so the first rain often will wash them off the surface of concrete. With the passage of time, efflorescence becomes lighter and less extensive unless there is an external source of salt. Light-colored surfaces show the deposits much less than darker surfaces. Most efflorescence can be removed by dry brushing, water rinsing with brushing, light waterblasting or light sandblasting, followed by flushing with clean water. If this is not satisfactory, it may be necessary to wash the surface with a dilute solution of muriatic acid (1 to 10 percent). For integrally colored concrete, only a 1 to 2 percent solution should be used to prevent surface etching that may reveal the aggregate and hence change color and texture. Always pretest the treatment on a small, inconspicuous area to be certain there is no adverse effect. Before applying an acid solution, always dampen concrete surfaces with clean water to prevent the acid from being absorbed deeply where damage may occur. The cleaning solution should be applied to no more than 0.4 m^2 (4 ft^2) at one time to avoid surface damage. Wait about 5 minutes, then scour with a stiff bristle brush. Immediately rinse with clean water to remove all traces of acid. The entire concrete element should be treated to avoid discoloration or mottled effects. Surfaces to be painted should be thoroughly rinsed with water and allowed to dry. See “Efflorescence: Causes, Prevention Repair,” *Concrete Technology Today*, PL871.

Low Spots

Low spots can affect slab drainage or serviceability if items placed on the slab need to be level. Low spots are often caused by poor lighting during placement and finishing, improperly set forms and screeds, damage to form and screed grade settings during construction, use of overly wet or variably wet concrete, and poor placement and finishing techniques.

Low spots can be avoided by (1) using a low-slump, low-water-content concrete mix, (2) providing adequate light, (3) frequently checking grades and levels, and filling the low areas, (4) using a vibrating screed for strikeoff, and (5) using a "highway" straightedge in lieu of a bullfloat to smooth and straighten the surface.

Figure 8. A popout is a small fragment of concrete surface that has broken away due to internal pressure, leaving a shallow, typically conical, depression. (0113)

Popouts

A popout is a conical fragment that breaks out of the surface of the concrete leaving a hole that may vary in size generally from 5 mm to 50 mm (1/4 in. to 2 in.) but up to as much as 300 mm (1 ft) in diameter (Fig. 8). Usually a fractured aggregate particle will be found at the bottom of the hole, with part of the aggregate still adhering to the point of the popout cone.

The cause of a popout usually is a piece of porous rock having a high rate of absorption and relatively low specific gravity. As the offending aggregate absorbs moisture or freezing occurs under moist conditions, its swelling creates internal pressures sufficient to rupture the concrete surface. Pyrite, hard-burned dolomite, coal, shale, soft fine-grained limestone, or chert commonly cause popouts. Popouts may also occur to relieve pressure created by water uptake of expansive gel formed during the chemical reaction between the alkali hydroxides in the concrete and reactive siliceous aggregates.

Most popouts appear within the first year after placement. Popouts caused by alkali-silica reactivity (ASR) may occur as early as a few hours to a few weeks, or even a year, after the concrete is placed. Popouts caused by moisture-induced swelling may occur shortly after placement due to the absorption of water from the plastic concrete, or they may not appear until after a season or year of high humidity or rainfall or after the concrete has been exposed to freezing temperatures. Popouts are considered a cosmetic detraction and generally do not affect the service life of the concrete.

The following steps can be taken to minimize or eliminate popouts:

1. Use concrete with the lowest water content and slump possible for the application.
2. Use a durable crushed-stone or beneficiated-aggregate concrete.
3. During hot, dry, and windy weather, cover the surface with plastic sheets after screeding and bullfloating to reduce evaporation before final finishing. This reduces the migration of alkalies to the surface due to drying and therefore helps reduce popouts caused by alkali-silica reactivity (ASR).
4. Do not finish concrete with bleed water on the surface.
5. Avoid hard-steel troweling where not needed, such as most exterior slabs.
6. Avoid use of vapor barriers. If required, cover the vapor barrier with 100 mm (4 in.) of compactible granular fill, slightly dampened, and choked off

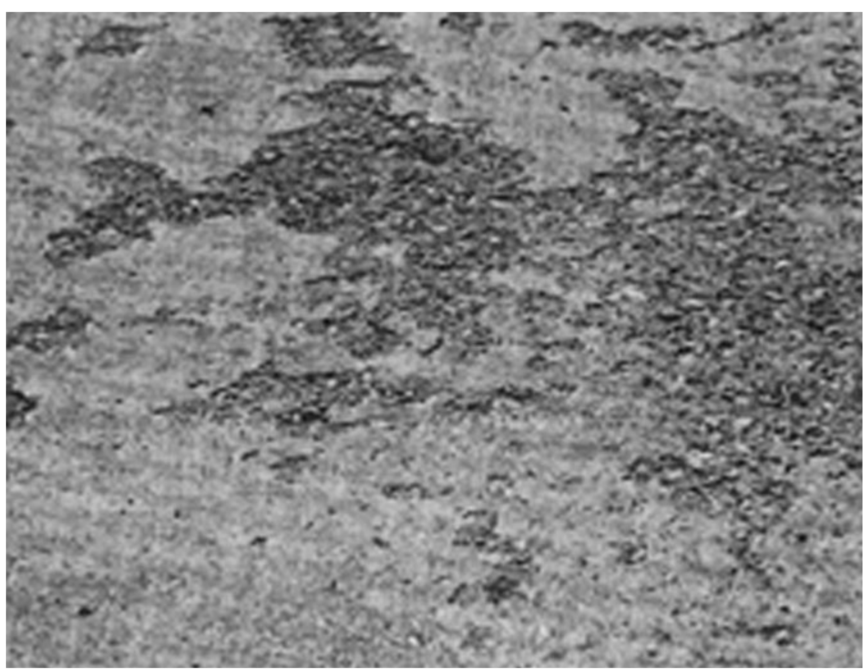

Figure 9. Scaling is a scabrous condition where the surface mortar has peeled away, usually exposing the coarse aggregate. (A5273)

with a fine-grade material to reduce friction between the base material and the slab. This material should be dry enough to act as a blotter for the concrete placed over it.

7. Use wet-curing methods such as continuous sprinkling with water, fogging, ponding, or covering with wet burlap soon after final finishing. Wet-cure for a minimum of 7 days, as wet cures can greatly reduce or eliminate popouts caused by ASR. Avoid plastic film, curing paper, and especially curing compounds as they allow an accumulation of alkalies at the surface. Flush curing water from the surface before final drying. Impervious floor coverings or membranes should be avoided as they can aggravate popout development.
8. Use a blended cement or a supplementary cementitious material such as fly ash (proven to control ASR) where popouts are caused by alkali-silica reactivity. Use of a low-alkali cement is also beneficial.
9. Use two-course construction with clean, sound rock in the topping, and the offending aggregates in the base slab, thus limiting the susceptible aggregate's exposure to excess moisture.
10. Slope the slab surface to drain water properly.
11. Use air-entrained concrete.
12. Reduce concrete temperature to 10°C to 20°C (50°F to 70°F).

Surfaces with popouts can be repaired. A small patch can be made by drilling out the spalled particle and filling the void with a dry-pack mortar or other appropriate patch material. If the popouts in a surface are too numerous to patch individually, a thin-bonded concrete overlay may be used to restore serviceability.

For more information on popouts, refer to "Popouts: Causes, Prevention, Repair," *Concrete Technology Today*, PL852.

Scaling and Mortar Flaking

Scaling is the general loss of surface mortar exposed to freezing and thawing. The aggregate is usually clearly exposed and often stands out from the concrete (Fig. 9). Scaling is primarily a physical action caused by hydraulic pressure from water freezing within the concrete and not usually caused by chemical corrosive action. When pressure exceeds the tensile strength of concrete, scaling can result if entrained-air voids are not present to act as internal pressure relief valves.

The presence of a deicer solution in water-soaked concrete during freezing causes an additional buildup of internal pressure.

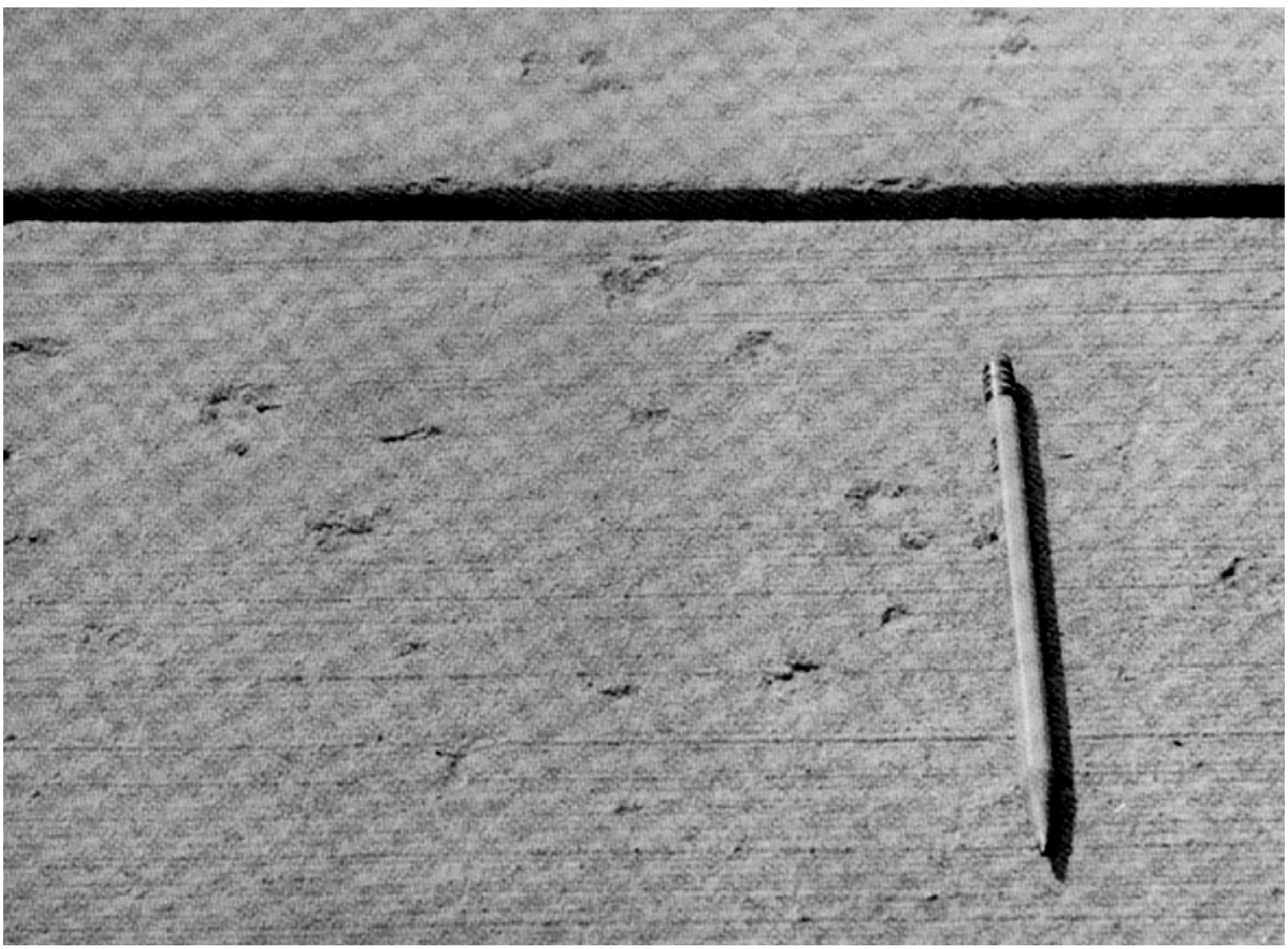

Figure 10. Mortar flaking over coarse aggregate. (52225)

Deicers such as sodium chloride, urea, and weak solutions of calcium chloride do not chemically attack concrete; however, deicers containing ammonium sulfate or ammonium nitrate will rapidly disintegrate concrete and should not be used. Several deicers, particularly those containing chloride, can also cause corrosion of embedded steel.

ACI 116R, *Cement and Concrete Terminology*, defines light, medium, severe, and very severe scaling as ranging from no exposure of coarse aggregate up to a loss of mortar and coarse aggregate particles to a depth of greater than 20 mm (0.8 in.).

Mortar flaking over coarse aggregate particles (Fig. 10), sometimes called popoffs, is another form of scaling that somewhat resembles a surface with popouts. However, mortar flaking usually does not result in freshly fractured aggregate particles and there are fewer, if any, conical voids such as those found in popouts. Aggregate particles with flat surfaces are more susceptible than round particles to this type of defect. Mortar flaking occasionally precedes more widespread surface scaling, but its presence does not necessarily lead to more extensive scaling.

Mortar flaking over coarse aggregate particles is caused essentially by the same actions that cause regular scaling. Excessive and early drying out of the surface mortar can alone aggravate scaling. However, the moisture loss is accentuated over aggregate particles near the surface. The lack of moisture necessary for cement hydration results in a mortar layer of lower strength and durability, higher shrinkage, and poorer bond with the aggregate. Upon freezing in a saturated condition, this thin, weakened mortar layer breaks away from the aggregate. Poor finishing practices can also aggravate mortar flaking.

Figure 11. A typical location for a spall is along a joint, usually the result of the joint functioning improperly. (67216)

Field service experience and extensive laboratory testing have shown that when properly spaced air voids are present, air-entrained concrete will have excellent resistance to surface scaling and mortar flaking due to freezing and thawing and the application of deicer chemicals, provided the concrete is properly proportioned, placed, finished, and cured. The following practices are recommended:

1. Use a proper concrete mix with durable and well-graded aggregate, a low slump—maximum of 100 mm (4 in.); adequate compressive strength prior to exposure to repeated cycles of freezing and thawing—a minimum of 28 MPa (4000 psi); low water-cement ratio—0.45 or less; purposely entrained air—5 to 8 percent total air content; and a minimum cementitious materials content of 335 kg/m^3 (564 lb/yd^3) of concrete. For concrete exposed to deicing chemicals, ACI 318/ACI 318R (ACI Building Code Requirements for Structural Concrete and Commentary) places a limit on the total allowable percentage of mineral admixture: 25% for fly ash, 50% for slag, and 10% for silica fume. Wet, sloppy, low-strength concrete with low cement content and without entrained-air voids is prone to scale at an early age, often after the first or second winter in severe climates where deicers are used.
2. Properly slope the concrete to drain water away from the slab; saturated concrete is much more susceptible to deterioration than drier concrete.
3. Use proper finishing practices. Concrete that is prematurely floated or troweled while added water or bleed water is on the surface tends to scale when subjected to saturated freezing. Remixing water into the top of the slab can cause the formation of a crust of surface laitance that will scale. In addition, finishing concrete before the bleed water comes to the surface can entrap water under the finished surface, forming a weakened zone or void, which can result in scaling or surface delamination.
4. Cure promptly with wet burlap (kept continuously wet), curing paper, or plastic sheet for a minimum of 7 days (longer when temperatures are around 4°C (40°F), or until the con-

crete attains 70 percent of the specified strength in cases where the curing period is followed by an air-drying period. Curing compounds may also be used on spring and summer placements.

5. After curing, allow the concrete 30 days to air dry. Concrete that may not have sufficient time to dry before being exposed to freezing temperatures, such as that placed later in the year, should not have deicing chemicals applied during its first winter season. Instead, if traction is required over ice or snow, sand can be used.

If scaling or mortar flaking should develop, or if the concrete is suspected of having poor quality, a breathable surface treatment may be applied to help protect the concrete against further freeze-thaw damage. These treatments are made with linseed oil, silane, siloxane, or other materials.

Oil treatment normally consists of two applications of equal parts of commercial boiled linseed oil and a solvent such as turpentine, naphtha, or mineral spirits. Recommended coverages are 9 to 11 m^2/liter (40 to 50 yd^2/gal) for the first application and about 15 m^2/liter (70 yd^2/gal) for the second application. The temperature of the concrete should be 10°C (50°F) or above at the time of application to assure proper penetration and to hasten drying. Applying a sealer is best done as the concrete is cooling down rather than heating up, which usually occurs in the early evening. This helps draw the sealer deeper into the concrete rather than allow the vapors to push it out of the pores. Since oil treatment will produce a slippery surface until absorbed, it may be necessary to keep traffic off the concrete until sufficient drying has taken place.

Impermeable materials, such as most epoxies, should not be used on slabs on ground or other concrete where moisture can freeze under the coating. The freezing water can cause delamination under the impermeable coating; therefore, a breathable surface treatment should be used.

Thin-bonded overlays or surface-grinding methods can usually remedy a scaled surface if sound, air-entrained concrete is present below the scaled surface.

Spalling

Spalling is a deeper surface defect than scaling, often appearing as circular or oval depressions on surfaces or as elongated cavities along joints. Spalls may be 25 mm (1 in.) or more in depth and 150 mm (6 in.) or more in diameter, although smaller spalls also occur. Spalls are caused by pressure or expansion within the concrete, bond failure in two-course construction, impact loads, fire, or weathering. Improperly constructed joints and corroded reinforcing steel are two common causes of spalls (see Figs. 11 and 12). If left unrepaired, spalls can accelerate pavement deterioration. However, shallow spalls along joints in roads, no more than 75 mm wide by 300 mm long (3 x 6 in.), often do not affect ride of automobiles, and are not repaired.

Spalls can be avoided by (1) properly designing the concrete element—including joints—for the environment and anticipated service, (2) using proper concrete mixes and concreting practices, and (3) taking special precautions where necessary. The first line of defense against steel corrosion caused by chloride-ion ingress (for example, from deicers) should be the use of a low permeability concrete made with a water-cement ratio of 0.4 or less. If steel reinforcement is used, it should have adequate cover as outlined in ACI 318. For extreme conditions, the addition of silica fume or latex to a concrete mix will dramatically lower its permeability. Other examples of special precautions to reduce steel corrosion induced by chloride-ion ingress in extreme conditions are (1) the use of epoxy-coated reinforcing

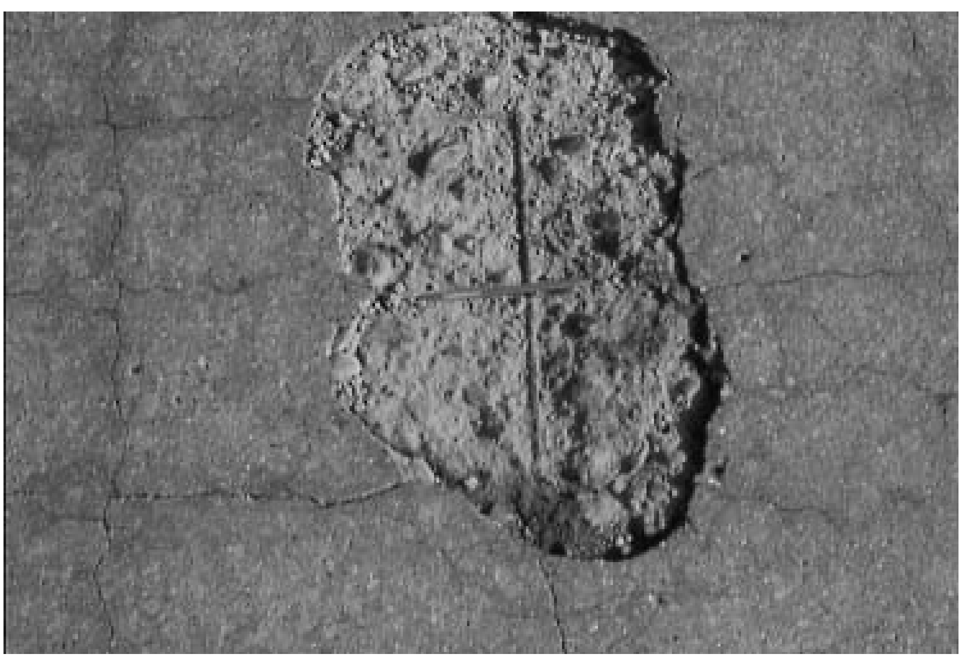

Figure 12. Corrosion of steel reinforcement is an expansive process, which can cause pressure within the concrete and lead to this type of concrete spall. (67217)

steel (ASTM D 3963), (2) application of breathable surface sealers such as silane, siloxane, and methacrylate-based compounds, (3) the use of corrosion-inhibiting admixtures, and (4) cathodic protection methods. These methods may be combined for added protection.

Spalled areas of concrete can be repaired when no more than the top 1/3 of the pavement is damaged and the underlying pavement is sound: if more than the top 1/3 of the pavement is damaged, if steel reinforcement bars are uncovered, or if spalls are a result of misaligned dowel bars or D-cracking, a full-depth repair is required. The economics of partial-depth repair versus complete replacement should be considered, as it may be more cost effective (and more uniform-looking) to replace the entire area.

Concrete should be removed to a depth of at least 40 mm (1-1/2 in.). The boundaries of the repair area should be determined by sounding the pavement for delaminated or unsound areas. Patch limits should be extended about 100 mm (4 in.) beyond the edges of the unsound areas. Spalled or delaminated concrete is removed by sawing and chipping or by milling. If jackhammers are used, they should be small—no greater than 15-kg (30-lb)—to prevent concrete damage beyond the repair area. It is best to keep the area rectangular or square and provide vertical edges at

Figure 13. Self-leveling toppings can be used to restore the floor surface on an otherwise sound slab. Underlayments usually require a floor covering material such as tile or carpet. (69682)

the boundaries to contain the patch. The exposed concrete should be lightly sandblasted to clean and roughen the surface so that good bond can be obtained with the repair material.

Patching materials can be portland-cement-based, rapid strength proprietary materials, or polymer concretes (epoxy, methyl methacrylate, and polyurethane). Bituminous materials have also been used, but are usually considered temporary. Patch materials should have a thermal expansion coefficient that is compatible with the underlying concrete. Some materials are formulated to work with a bonding agent; other materials require only a clean surface for good bond. Patch materials are usually mixed in small quantities to assure prompt placement (without segregation), consolidation, finishing, and curing. The air temperature at placement needs to be above 4°C (40°F) for all cement-based patches and many of the proprietary rapid-setting mixes. The polymer concretes can be applied at lower temperatures and to wet substrates, but perform better when placed under more favorable conditions. Wet curing methods (spraying, wet coverings) reduce shrinkage of patch materials more than sealed curing (sheet materials, curing compounds). When spall repair involves a joint, the joint must be restored to proper working condition to allow for thermal expansion of the slab. This is one of the most important steps to ensure that partial-depth repairs will function properly. Sealants placed in joints keep out noncompressible materials and allow free joint movement. Consult manufacturers for further recommendations on patching materials and placement methods.

Thin Toppings and Underlayments

A number of proprietary materials are available for topping and underlayment of concrete slabs. These materials are generally portland-cement-based, nonshrink, and are frequently self-leveling (Fig. 13). They are primarily used to restore the floor surface on an otherwise sound slab. Topping materials provide the wearing surface, and underlayments require a floor covering material such as tile or carpet. Applications less than 25-mm (1-in.) thick are normally bonded to the slab and require a primer for this purpose. Thicker applications—up to 100 mm (4 in.)—may or may not require a primer. Adding aggregate to the formulation reduces shrinkage. Consult the manufacturer on the use and installation of these products. See *Resurfacing Concrete Floors* (IS144) for more information.

Analysis of Surface Defects

The cause of most concrete defects can be determined by petrographic (microscopical) analysis on samples of the concrete (Fig. 14). A petrographic analysis of concrete is performed in accordance with the American Society for Testing and Materials' Standard Practice for Petrographic Examination of Hardened Concrete, ASTM C856.

Samples for the analysis are usually drilled, 100-mm (4-in.) diameter cores or saw-cut sections. Broken sections can be used, but cores or saw-cut sections are preferred because they are less apt to be disturbed. Samples should represent concrete from both problem and nonproblem areas. The petrographer should be provided with a

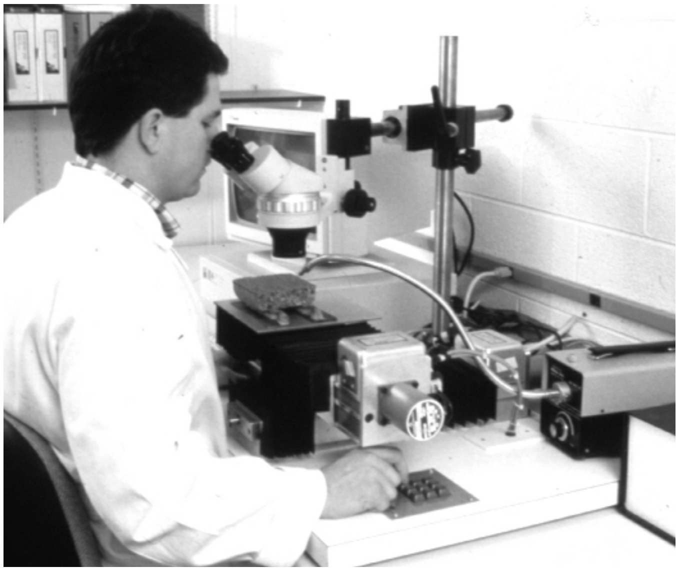

Figure 14. The cause of most concrete surface defects can be determined by petrographic analysis. (64241)

description and photographs of the problem, plus information on mix design, construction practices used, and environmental conditions. A field review by a petrographer, engineer, or concrete technologist is also helpful in analyzing the defect.

The petrographic report often includes the probable cause of the problem, extent of distress, general quality of the concrete, and expected durability and performance of the concrete. Corrective action, if necessary, would be based to a great extent on the petrographic report. Additional information on petrography is available through the Portland Cement Association.

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Miller, F. MacGregor, Powers, Laura J., and Taylor, Peter C., *Investigation of Discoloration of Concrete Slabs*, Serial No. 2228, Portland Cement Association, 1999, 22 pages.

Taylor, Peter C., Detwiler, Rachel J., and Tang, Fulvio J., *Investigation of Discoloration of Concrete Slabs (Phase 2)*, Serial No. 2228b, Portland Cement Association, 2000, 22 pages.

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The Homeowner's Guide to Building with Concrete, Brick & Stone, SP038
Concrete Repair and Material Considerations, SS374 (slide set)
Surface Defects, SS380 (slide set)
Guidelines for Partial-Depth Repair, TB003 (American Concrete Pavement Association)
Concrete Petrography, John Wiley & Sons Inc., LT226

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