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Identification and Control of Visible Effects of Consolidation on Formed Concrete Surfaces

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This report provides guidelines for identifying and controlling visible effects of consolidation on precast or cast-in-place formed concrete surfaces. It includes a summary of direct and indirect causes of such imperfections. An outline to assist in the reporting on surfaces and photographs to illustrate typical concrete surface blemishes are also included.

Surface blemishes in concrete may be minimized by proper planning during the design and specification stages. Of equal importance is the employment of properly trained and motivated supervisory and non-supervisory construction personnel to achieve the intended concrete finishes and surface textures.

The report emphasizes significant consolidation factors that minimize undesirable surface effects. The reader is cautioned that other potential causes of such effects may exist beyond those listed in this report. There are documents in which a feature designated as a defect is one that must be prevented, avoided, corrected, remediated or otherwise dealt with. The term "defect," as formerly used in this report, covers blemishes and departures from perfection that are not features, and must be avoided or repaired whenever they occur. Some surfaces can tolerate them to some or any degree; other surfaces cannot. It is the responsibility of the specifier to indicate in the contract documents what constitutes acceptable and unacceptable blemishes for the various surfaces to be produced under the terms of a given contract. Terms used in this report are as defined in ACI 116R.

Keywords: aggregates; bugholes; concretes; consistency; consolidation; construction joints; discoloration; formwork (construction); mix proportioning; placing; preplaced-aggregate concrete; quality control; surface defects; temperature; vibration; voids; workability.

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CHAPTER 1—GENERAL

A formed concrete surface, uniformly smooth or deeply textured and essentially free of blemishes and color variation, is difficult to attain. Since repairs to a defective surface are costly and seldom fully satisfactory, the need for repairs should be minimized by establishing and maintaining the quality of the concrete operation and by adhering to acceptable consolidation procedures. Standards for surface finishes are beyond the scope of this report. Guidance for establishing appropriate standards is offered by the International Council for Building Research (CIB) (1975), which classifies formed surface finishes as follows:

- Special—High standards of appearance required (ACI 303R);
- Elaborate—Definite requirements for visual appearance;
- Ordinary—Appearance is of some importance; and
- Rough—No special requirements for finish.

Concrete construction procedures do not always provide the control necessary to consistently obtain blemish free concrete indicated by a special category.

To achieve any concrete finish, the designer and the contractor must use materials as well as design and construction practices that will keep surface effects within acceptable limits. There is a definite need for understanding the causes of unacceptable blemishes and effects encountered in concrete construction and a need for applying more effective measures to minimize or eliminate them. This report addresses those needs and its major emphasis is on consolidation-related effects.

The most serious effects resulting from ineffective consolidation procedures are: honeycomb, subsidence cracks, cold joints, and excessive surface voids. A detailed description of the blemishes and their causes are provided in Table 1. Some imperfections may not conform to contract documents and may be considered as defective work.

CHAPTER 2—FACTORS CAUSING EFFECTS

Causes of consolidation-related effects on formed concrete surfaces (Table 1) include:

A. Design and construction-related causes
- Difficult placement due to design of a member
- Improper selection of horizontal construction joint location
- Improper design, manufacture, installation, shipping, preparation and maintenance of forms
- Improper selection of concrete mixture proportions
- Failure to adjust concrete mixture proportions to suit placement condition
- Improper placement practices
- Improper consolidation practices
- Improper steel detailing

B. Equipment-related causes
- Improper equipment
- Improper equipment maintenance
- Equipment failure (crane, pump, concrete plant)
- Interruption of utility service

C. Material-related causes
- Improper selection of release agent
- Cement characteristics
- Variation in mixture constituents
- Inappropriate use of admixtures

D. Environmental causes
- Extreme weather conditions

Examples of some of the more common blemishes are illustrated in Fig. 1 through 10.

2.1—Design of structural members

The common problems requiring consideration during design and planning are congested reinforcement (particularly splices), narrow sections, or complex form configurations. Conditions that require closed top forming, embedments, and battered forms also require consideration during design and planning.

To produce properly consolidated concrete with the desired appearance, the placement and consolidation of the concrete must be understood. The designer must have a working knowledge of the concrete placement process. The designer and the constructor should communicate during the early phases of the concreting process. Early recognition of problem areas is important to provide time to take remedial measures, such as staggering splices, grouping reinforcing steel, modifying stirrup spacing, increasing the section size, and selecting locations of horizontal construction joints. When unfavorable conditions exist that could contribute to substandard surfaces, one or more of the following actions should be taken:

1. Redesign the member;
2. Redesign the reinforcing steel;
3. Provide adequate access for consolidation at horizontal construction joints;
4. Modify mixture proportions;
5. Use mock-up tests to develop a procedure; and/or
6. Alert the constructor to critical conditions.

Table 1—Summary of primary causes of surface effects

Defects			Causes					
Name	Description	Fig.	Design of members 1	Forms 2	Construction conditions 3	Properties of fresh concrete 4	Placement 5	Consolidation 6
Honeycomb	Stony zone with air voids; lacking in fines. Due to segregation	1	Highly congested reinforcement, narrow section, internal interference, reinforcement splices, restricted access for vibration, high monolithic lifts	Leaking at joints, severe grout loss	Premature setting reinforcement too close to forms, lack of access for vibration, congestion due to splices	Insufficient fines, low workability, early stiffening, excessive mixing, too large aggregate for placing conditions	Excessive free fall, excessive lift of concrete in forms, drop chute omitted, or insufficient length, too small a tremie, segregation due to horizontal movement	Vibrator too small, frequency and amplitude inappropriate, too short immersion time, excessive spacing between immersions, inadequate penetration insufficient number of vibrators
Air surface voids	Small individual holes, irregular, ranging up to 1 in. (25 mm) in diameter	2	Battered or interfering construction	Form face impermeable, poor wetting characteristics, formwork too flexible, use of improper form release agent	Excessive release agent, high temperature of concrete.	Low FM of fine aggregate, lean, fine aggregate with a high FM, low workability, excessive cement or pozzolan, particle degradation, excessive sand, high air content	Too slow, caused by inadequate pumping rate, undersized bucket	Too large an amplitude, external vibration inadequate, head of vibrator partially immersed
Form-streaking	Fine aggregate or coarse aggregate textured areas lacking cement, usually associated with dark color on adjacent surface	3		Leaking at joints, tie holes, caused by loose hardware or oversized tie holes	Usually caused by horizontal concrete movement	Excess water or high slump	Improper timing between placing and vibrating	Excessive amplitude or frequency for form design
Aggregate transparency	Dark or light areas of similar size and shape to that of the coarse aggregate, mottled appearance	4		Too flexible, high-density surface finish		Low fine-aggregate content, gap-graded aggregate dry or porous aggregate, excessive coarse aggregate, excessive slump with lightweight concrete		Excessive external vibration; overvibration of lightweight concrete
Subsidence cracking	Short cracks varying in width, more often horizontal than vertical	5	Interference to access, lack of adequate cover	Poor thermal insulation, irregular shape restraining settlement, excessive absorbency	Insufficient delay between top-out of columns and placement of slab or beam, low humidity	Low fine aggregate, high water content, too high slump, Poorly proportioned mixes	Too rapid	Insufficient vibration and lack of revibration

2.2—Specifications

Acceptable specifications for concrete and concrete construction are essential to ensure proper construction practices. Practical and workable specifications that allow for unusual and complex job conditions are needed.

Specifications should be sufficiently broad in scope to permit adjustments of mixture proportions and batch adjustments needed to produce uniformly workable concrete that will respond readily to vibration. Concrete may still vary due to changes in aggregate grading, ambient and concrete temperature, air content, and batch quantities, even though these changes are within specification limits. Accepted mixture proportions may need adjustments to produce the desired concrete characteristics and to minimize consolidation problems. However, the mixture should be adjusted with care to maintain the design intent and to avoid other problems, such as excessive cracking. The specifications should require mixing, transporting, handling, and placing that can result in adequate consolidation and minimize chances for surface blemishes. Moreover, the specifications should call for vibrators of proper size and characteristics, as recommended in ACI 309R. Small-diameter vibrators should be required to supplement larger-diameter vibrators where access is limited.

Table 1—Summary of primary causes of surface effects (cont.)

Defects			Causes					
Name	Description	Fig.	Design of members 1	Forms 2	Construction conditions 3	Properties of fresh concrete 4	Placement 5	Consolidation 6
Color variation	Variations in color of the surface, visible within a few hours after removing the formwork	6	Heavy reinforcement close to forms	Variation in absorptive capacity of surface, reaction with form face, chemical reaction with release agents, leakage of forms at joints and tie holes		Non-uniform color of materials, inconsistent grading, variation in proportions, incomplete mixing. Calcium chloride can cause darker color. Too high a slump. Over-manipulation	Segregation slump too high	Vibrator too close to form, vibration next to forms variable
Sand streaking	Variation in color or shade due to separation of fine particles	7		Form leakage. Excess water at bottom of form forced up along form face by hydraulic pressure	Low temperature, wet mixtures	Lean "over-sanded" mixtures and harsh, wet mixtures deficient in fines	Too rapid for type of mixture	Excessive vibration. Excessive amplitude. Over-manipulation
Layer lines (pore lines)	Dark colored zones between concrete layers	8	Internal interference		Insufficient planning, high temperature	Wet mixture with tendency to bleed	Slow placement, lack of equipment or manpower	Lack of vibration, failure to penetrate into previous layer
Cold joints	Voids, honeycomb and color variations along boundaries of lifts, top layer of concrete not adequately bonded to substrate	9	Insufficient space to insert vibrator		Poor planning or insufficient backup equipment, substrate concrete has set	Too dry, early stiffening, slump loss	Delayed delivery, lifts too thick	Failure to vibrate into lower lift. Insufficient vibration
Form offsets	Abrupt to gradual surface irregularities	10	Construction joint at change in direction of formwork	Inadequate formwork design for rate of placement	Poor form anchorage and inadequate bulkheads	Excessive retardation of time of setting of concrete	Rate too high	Excessive amplitude, non-uniform spacing of immersion horizontal movement of concrete

2.3—Forms

Some surface blemishes are caused by inadequacies of the formwork. Examples are leakage at joints, inadequate facing material, excessive overload on previously placed concrete (ACI 303R), inadequate anchorage, poorly braced and excessively flexible forms, improper use of release agents, and oversized and unsealed tie holes. Surface blemishes also result from overuse of forms, poor storage practices, inadequate cleaning, and improper patching and repair of the forms.

The number of visible surface voids (bug holes) may be reduced by using absorptive forms; however, smooth forms in combination with the correct selection of a form release-agent allow air voids at formed surfaces to move upward more freely. ACI 303R discusses the use of release agents.

Some dry resin-based release agents used on steel forms will greatly increase the number of bug holes. An excessive amount of release agent collecting in the bottom of the form may result in discoloration of the concrete and may create weak areas. Inadequately cleaned forms, or those which have been reused too many times, can contribute significantly to the formation of surface blemishes. When any of these conditions occurs, the concrete surface may peel during form removal.

The finish should be observed as the form is stripped so that appropriate corrective measures, if needed, can be implemented promptly. Inward sloping forms have a tendency to trap or restrict the movement of entrapped air and bleed water to the surface, and increase the occurrence of surface effects. Form strength, design, and other form requirements are covered in ACI 347R.

2.4—Properties of fresh concrete

The composition, consistency, workability, and temperature of fresh concrete has a significant bearing on the ease with which a concrete mixture may be placed and consolidated. For critical surface finishes, the effect of each ingredient of the mixture may require special consideration. Placing conditions should also be considered during mixture proportioning.

Mixture adjustments should be made to the proportions to maintain workability when materials and field conditions change, provided that critical properties, such as durability and strength, are maintained.

A review by the designer is essential to ensure that strength levels, nominal maximum aggregate size, and slump requirements for different structural elements are met. Concrete ingredients should be evaluated and proportions should be selected well in advance of the concreting operation to achieve the desired properties for the fresh concrete. Sticky mixtures may occur if the fine aggregate grading in the 1.18 mm to 300 μm (No. 16 to 50) size range approaches the upper limits specified by ASTM C 33, or if high cement contents are used. Some pozzolans also may cause mixtures to be more cohesive. Thus, the passage of entrapped air may be restricted and air voids may be trapped at the interface between the concrete and the form. If fine aggregate contains the proper amount of materials in the 600 to 300 μm (No. 30 to 50) size range, little bleeding will occur in the resulting concrete. As a result, placement and consolidation of the concrete will be facilitated, thereby minimizing surface effects.

Soft aggregates may degrade and produce additional fines. In some instances, the fines may make the mixture more cohesive and increase the difficulty of removing entrapped air. This is particularly true at high cementitious materials contents. In other instances, the additional fines can significantly increase the water demand, resulting in lower strength, increased shrinkage, and crazing of smooth formed surfaces. Experience indicates that a concrete at a given consistency will generally flow more easily at lower temperatures than at higher temperatures.

When chemical and especially mineral admixtures are used, their effect on placement and consolidation should be evaluated when mixture proportions are being established. All of the factors discussed above need to be considered to obtain a concrete mixture with the desired composition, consistency, and workability to facilitate its placement and consolidation.

2.5—Placement

Concrete should be placed as quickly as possible with a minimum amount of segregation and spattering on the forms. Once the coarse aggregate is separated from the mortar by poor handling and placement practice, it is virtually impossible to work the mortar back into the voids and restore a dense mass by vibration. Segregation and separation cause honeycomb. Spattered mortar on the form produces color variations and poor surface texture. Placing concrete too slowly may allow workability to be lost and can produce layer lines or cold joints due to improper consolidation. The rate of placement and vibration factors (intensity and spacing) should be selected to minimize entrapped air in the concrete.

If concrete is deposited in thick layers of more than 300 mm (12 in.), more air may be trapped than if it is placed in a thinner, even layer since the air has to travel farther to escape. Where mixtures of dry or stiff consistencies are required, the placement rate should be slower to permit adequate consolidation so as to avoid bug holes and honeycombing. However, in the case of a sanitary treatment structure with steel forms, an increase in lift thickness from 0.6 to 1.2 m (2 to 4 ft) reduced bug holes by 50 percent when an air content of 5 percent was specified.

2.6—Consolidation

Concrete consists of coarse aggregate particles in a matrix of mortar, and irregularly distributed pockets of entrapped air. If the concrete is air entrained, an additional evenly distributed system of entrained air bubbles is present. The volume of entrapped air in unconsolidated concrete may vary from about 5 to 20 percent depending on the workability of the mixture, size and shape of the form, amount of reinforcing steel, and method of depositing the concrete. The purpose of consolidation is to remove as much of this entrapped air as practical.

Vibration is the most common method of consolidation. It causes very rapid movement of the concrete mixture particles and briefly liquefies the mixture, thus reducing the internal friction. When vibrated, concrete becomes fluid and through the action of gravity seeks a lower level and denser condition as entrapped air rises to the surface and is expelled. It compacts laterally against the form and around the reinforcing steel. In practice, vibration is normally continued until the entire placement acquires a uniform appearance and its surface just starts to glisten or large bubbles cease to appear. A film of cement paste should be discernible between the concrete and the forms. These visual indicators are not necessarily an accurate indication of good consolidation. ACI 309R provides guidance on judging the adequacy of vibration.

Undervibration is far more common than overvibration, and may be caused by the following:

1. Use of an undersized, underpowered, or poorly maintained vibrator;
2. Excessive or haphazard spacing of vibrator insertions;
3. Inadequate vibration during each insertion;
4. Failure of the vibrator to penetrate into the preceding layer; and/or
5. Vibrator in the wrong position relative to the form.

Common imperfections resulting from under-vibration are honeycomb, excessive entrapped air voids, and layer lines.

Overvibration can occur if vibration is continued for a prolonged time (several times the recommended time period). Overvibration is generally the result of using oversized equipment, improper procedures, high slump, or improperly proportioned mixtures. It may result in segregation, excessive form deflection, sand streaking, and form damage. Backstrom et al. (1958) found that air content of concrete is decreased by increasing periods of vibration, but little effect is noted on spacing factor of air-entrained concrete. In concrete of nominal 6.5 percent air the air content dropped from 6.7 to 1.2 after 2, 6, 12, 20, 30, and 60 sec of vibration, but the spacing factor was unchanged as was the number of cycles to 25 percent loss in mass.

The consequences of overvibration will be minimized if a well-proportioned mixture with a proper slump is used. The

Fig. 1—Honeycomb.

behavior of fresh concrete during vibration is discussed in ACI 309.1R.

2.7—Special construction conditions

No matter how carefully a concrete finish is specified, the resultant quality depends on careful construction site organization and the use of well-trained and skilled workmen. Competent supervision is essential to assure that the construction forces properly handle and assemble the forms and methodically place and consolidate the concrete. Supervisors must be alert to unfavorable conditions during the installation of forms and reinforcement and immediately bring these conditions to the attention of the designer. The designer should also locate horizontal construction joints at points of maximum access for placement and consolidation exists. Combining lifts may restrict access for proper consolidation and increase the likelihood of surface effects.

Formed concrete surfaces under box outs and battered forms require special considerations for placement. The mixture may have to be adjusted to produce a readily flowable concrete that is capable of completely filling the formed area. For large surface areas, it may be necessary to cut holes in a battered form to provide access for vibrating the concrete. With thin layers and careful vibration, the air bubbles can be drawn up the side of the form. Experience shows that sloped concrete steeper than about 20 deg from horizontal should be formed and the concrete thoroughly vibrated to minimize surface voids. Sloping forms at angles of about 45 deg from horizontal or less may be erected as temporary forms that are removed after initial setting for later hand finishing of the concrete.

Large mass-concrete sections placed in irregularly shaped forms may have surface blemishes due to non-uniform or widely spaced locations for tremies, pipes, or chutes. Poorly planned and executed procedures can cause the concrete to build up in piles. This will promote segregation, cold joints, layer lines, honeycomb, and subsidence cracks. To obtain acceptable results, placing methods must be well planned and well supervised.

CHAPTER 3—SURFACE BLEMISHES

Surface blemishes that can result from ineffective consolidation procedures are discussed below.

3.1—Honeycomb

Honeycomb (Fig. 1) is a condition of irregular voids due to failure of the mortar to effectively fill the spaces between coarse aggregate particles. Where bridging of the coarse aggregate particles or stiffness of the mixture is a cause of honeycomb, vibration may assist in overcoming the bridging by increasing the flowability of the concrete. Factors that may contribute to honeycombing are: congested reinforcement, segregation resulting in insufficient paste content, and improper fine aggregate to total aggregate ratio, improper placing techniques, rapid stiffening of hot concrete, difficult construction conditions, and insufficient consolidation effort. Changes in construction practices and in mixture proportions to improve workability and the use of water-reducing admixtures to increase slump may assist in reducing or preventing honeycombing.

3.2—Air voids in formed surfaces

Bug holes (Fig. 2) are small regular or irregular cavities, ranging from nearly invisible to 25 mm (1 in.) but usually not exceeding 15 mm (9/16 in.) in diameter, that result from entrapment of air bubbles in the surface of formed concrete during placement and consolidation. Bug holes on vertical faces are more likely to occur in sticky or stiff concrete mixtures of low workability that may have an excessive fine aggregate content or entrapped air content, or both. Also, the use of vibrators with too high of an amplitude or the lack of complete insertion of the vibrator head may result in an increased quantity of air-voids. Air voids vary in size from microscopic to about 25 mm (1 in.). Excess water normally manifests itself in other textural effects such as bleeding channels or sand streaks on vertical formed surfaces. Bleed water voids can form at the top of a column and on battered formed surfaces. Surface voids can be minimized by the procedures discussed in Section 4.

3.3—Form streaking

Form streaking (Fig. 3) is caused by mortar leaking through form joints and tie holes and may be aggravated by overvibration from vibrators that are too powerful, or by using forms that vibrate excessively during consolidation.

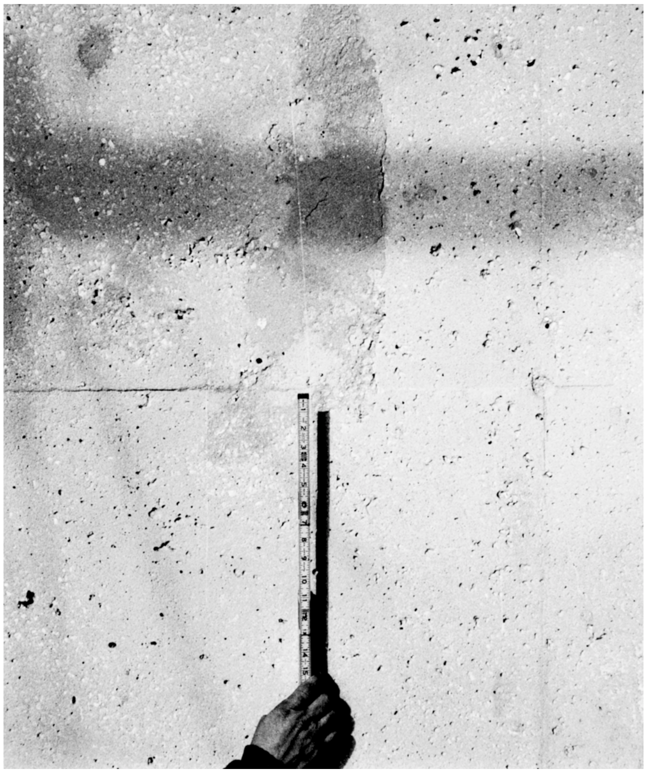

Fig. 2—Air surface voids.

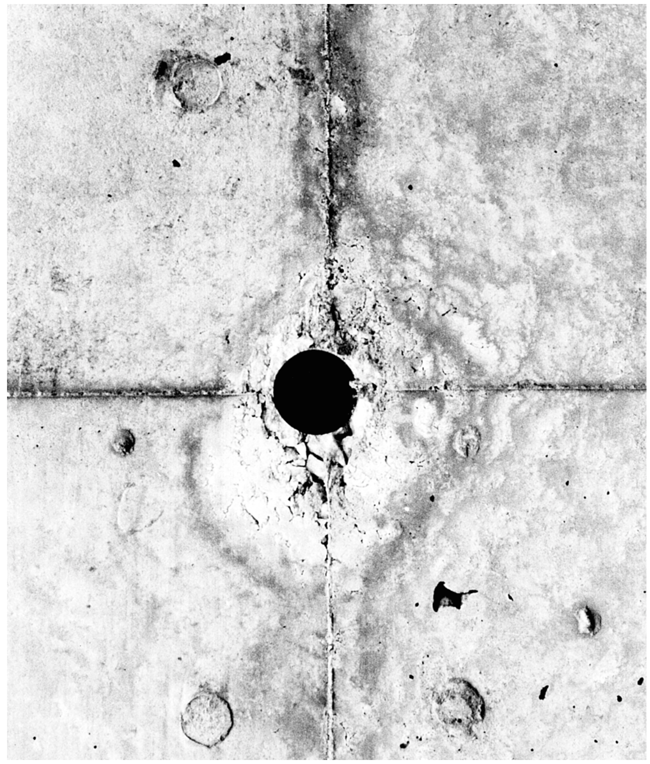

Fig. 3—Form streaking.

Placing excessively wet or high-slump concrete mixtures will result in more mortar washing out through tie holes and loose fitting forms. Special care is sometimes required when high-range water-reducing admixtures are used, as they tend to increase leakage at form joints.

3.4—Aggregate transparency

Aggregate transparency (Fig. 4) is a condition characterized by a mottled appearance on the surface that results from deficiencies in the mortar. It may occur when concrete mixtures have low fine aggregate content, dry or porous aggregates, or high slump with some lightweight and normalweight aggregates. Also, high density or glossy form surfaces may cause aggregate transparency.

3.5—Subsidence cracking

Subsidence cracking (Fig. 5) results from the development of tension when the concrete settles closed to after time of initial setting. Cracks are caused because the upper concrete bridges between the forms while the lower concrete settles. These cracks may occur when there is an insufficient interval between placing the concrete in the columns and placing the concrete for the slabs or beams. They may also occur adjacent to block-outs or over reinforcing bars with shallow cover.

To prevent subsidence cracking, the concrete can be revibrated. Revibration is most effective when done at the latest time at which the vibrator head will readily penetrate the concrete under its own weight. Subsidence cracking over reinforcing bars can be controlled by increasing concrete cover during the design phase and by using low-slump concrete that is well-consolidated.

3.6—Color variation

Color variation (Fig. 6) may occur within a placement if the concrete is not uniform or is incompletely mixed.

Vibrators inserted too close to the form can cause color variation by marring the form surface. External vibration used haphazardly may also cause color variation. Furthermore, color variations may result from nonuniform absorption, nonuniform application of the release agent, or both.

3.7—Sand streaking

Sand streaking (Fig. 7) is a streak of exposed fine aggregate in the surface of the formed concrete caused by heavy bleeding along the form.

It frequently results from the use of harsh, wet mixtures, particularly those deficient in the 300 to 150 μm (No. 50 to No. 100) and smaller sizes. Streaking tendencies increase when the ratio of fine aggregate to cementitious materials increases, such as in lean mixtures. Although the characteristics of Portland cement and pozzolans, if used, have some influence on bleeding, the grading of the fine aggregate is of greater importance. Sand streaking is controlled by the use of tight forms, proper mixture proportioning, and using well-graded fine aggregate to minimize bleeding. Streaking can be aggravated by excessive vibration, overmanipulation of the vibrator, the use of a vibrator with excessive amplitude; or excess water at the bottom of the form forced up along the form face by hydraulic pressure.

Fig. 4—Aggregate transparency.

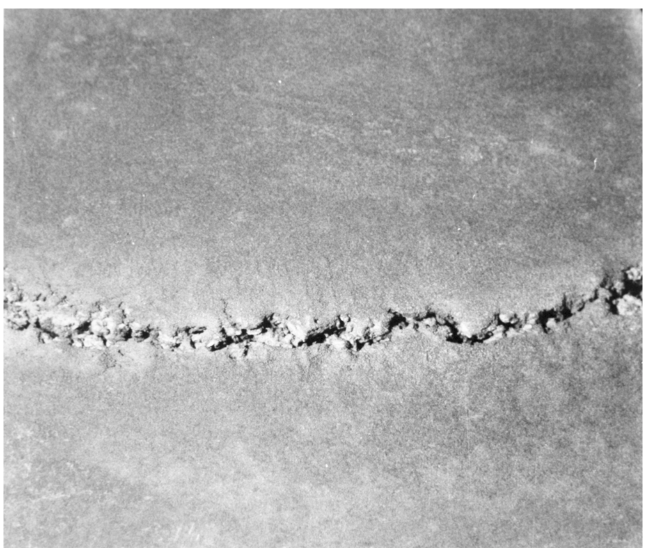

Fig. 5—Subsidence cracking.

3.8—Layer lines

Layer lines (Fig. 8) are dark horizontal lines on formed surfaces that indicate the boundary between concrete placements. Layer lines are caused by premature stiffening or insufficient consolidation of the previous layer of concrete due to lack of penetration of the vibrator into that layer, or the use of a mortar bonding layer between placements.

3.9—Form offsets

Form offsets (Fig. 9) are usually caused by inadequate stiffness or anchorage of the forms and can be aggravated by an excessive rate of placement or by using an excessively powerful vibrator, or both.

Fig. 6—Color variation.

3.10—Cold joints

Cold joints (Fig. 10) can often be avoided by contingency planning, backup equipment, working to keep the concrete surface alive, the use of retarding admixtures, and working the vibrator into lower lifts.

CHAPTER 4—MINIMIZING SURFACE EFFECTS

A number of studies have been made to determine how to achieve better consolidation resulting in fewer surface blemishes (Shilstone, 1977; Stamenkovic, 1973; Samuelson, 1970; and Reading, 1972). To minimize the size and number of bug holes and all other effects, the following practices should be followed:

- Vibration period should be of sufficient duration;
- Vibrator insertions should be properly spaced and overlapped and the vibrator removed slowly;
- Each concrete layer should be consolidated from the bottom upward;
- Vibration periods should be increased on withdrawal when using impermeable forms that permit air trapped at the form surface to escape through joints as between;
- Inward sloping forms and other complex design details should be avoided;
- Depth of placement layers should be limited;
- Vibrator should penetrate into the previous layer;
- Tightening devices and gaskets to prevent leakage at form joints should be provided as necessary; and
- Placing ports should be designed into the forms as necessary.

Where practical, bug holes can be minimized by the use of a 65-mm-(2-1/2 in.-)-diameter vibrator of high frequency

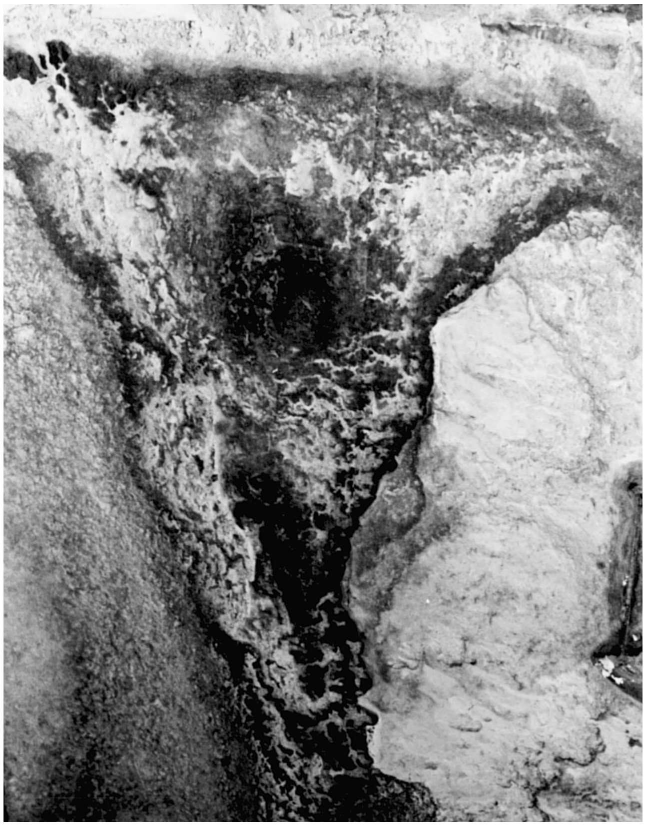

Fig. 7—Sand streaking.

with medium to low amplitude. The vibrator should be immersed in the concrete around the perimeter of the form without damaging the form. Where reinforcement is placed near the form wall, the vibrator must be inserted inside the reinforcement. Care should be taken to ensure that the vibrator has a sufficient radius of action to liquefy the concrete at the form.

Form vibration may be used to supplement the internal vibration. However, doing so may cause a major increase in form pressure. An alternate procedure is to use a high-frequency, low-amplitude form vibrator. Vibration procedures should be evaluated at the beginning of a project to determine the vibration time for each type of vibrator for a given mixture. Guidance on the selection of appropriate vibration amplitudes, frequencies, and equipment is given in ACI 309R.

In areas where surface air voids are most prevalent, revibration may be used to reduce them. Revibration is more effective if it is done at the latest possible time at which the vibrator head will readily penetrate the concrete under its own weight. Greater benefits are obtained with higher slump concrete mixtures, especially in the upper portion of a placement where excessive entrapped air voids are most prevalent. However, this practice may increase laitance that must be removed from horizontal construction joints. And may create color non-uniformity.

Other measures, such as altering mixture proportions, using high-range water-reducing admixtures, and using smaller nominal maximum size aggregate to improve workability

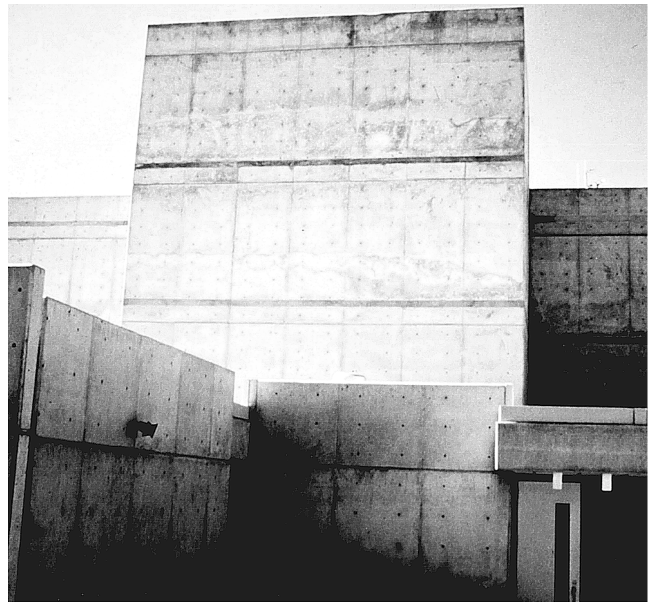

Fig. 8—Layer lines.

Fig. 9—Form offsets.

Fig. 10—Cold joints.

should also be considered as methods of minimizing surface effects, provided that design requirements are met. These measures have often been successful, particularly when trying to consolidate concrete in congested areas. Further guidance can be obtained from ACI 309R.

CHAPTER 5—CONSOLIDATION OF PREPLACED-AGGREGATE CONCRETE

The causes and cures of blemishes in concrete produced by the preplaced-aggregate (PA) concrete method (ACI 304.1R, Chapter 7) are different from conventionally mixed and placed concrete in certain aspects.

The rate of grout rise in preplaced aggregate should be about 0.3 m/min (1 ft/min) with a maximum of 0.6 m/min (2 ft/min). If the supply is too rapid, the grout will rise faster through the large voids and cascade into the smaller ones, trapping air. The result is spotty honeycombing. To avoid the occurrence of layer lines, the lower ends of the grout injection ports should always be maintained at least 0.3 to 0.6 m (1 to 2 ft) below the grout surface.

Grout will not penetrate pockets of fine aggregate; fines that collect against side or bottom forms will produce honeycombing. Also, care should be taken to ensure that coarse aggregate fills the space between the reinforcement and forms, and that no large voids are left that will be subsequently filled with grout. Large surface areas of grout not subdivided by coarse aggregate may show crazing from drying shrinkage.

Coarse aggregate should be saturated when placed and at the time it is grouted. If rewetting in the forms is required, a fog spray may be applied sparingly to dampen the upper 0.3 m (1 ft) or so. If the entire mass of aggregate needs re-wetting, the forms should be inundated with water from the bottom, then drained off slowly. Large quantities of water applied to the top of the aggregate will wash fines to the bottom, resulting in a poor surface or honeycomb.

Light vibration of forms with external vibrators permit the grout to cover the points of coarse aggregate in contact with the form. Overvibration of the form should be avoided, however, as it will induce bleeding that may result in sand streaking. Some trial and error may be required to determine the optimum amount of form vibration. Form design must be in conformance with increased pressure. Bolted connections in formwork require lock washers or double nutting. Formwork under external vibration requires positive attachment to footing or previous placement.

Where the appearance of formed surfaces is important, a test section of comparable height should be produced, the surface examined, and adjustments made to grading, placing, and consolidation procedures adjusted to obtain an acceptable result.

CHAPTER 6—CONCLUSION

Faulty design and construction practices can result in blemishes in formed concrete surfaces. To keep these effects within tolerable limits, an awareness of their causes and their cures is essential. The causes of these effects may lie in initial design concepts, specification, materials selection, proportioning, placement, consolidation, or workmanship. Frequently, the services of a specialist in concrete and concrete construction can be used to assist in obtaining concrete surfaces conforming to the higher standards. The execution of the work by well-trained work crews under competent supervision will ensure a concrete surface meeting the requirements of the owner or designer.

CHAPTER 7—SURFACE CONDITION OUTLINE

The following is an outline of items that should be considered by designers and constructors when reporting on the condition of a concrete surface and the possible causes of effects. By following this checklist and referring to earlier chapters in this document, the designer or constructor should then be in a position to identify the cause and correct most types of surface effects.

1—Description of structure
1.1—Name, location, type, and size
1.2—Owner, project engineer, contractor
1.3—Design
1.3.1—Architect and/or engineer
1.4—Photographs
1.4.1—General view
2—Description of wall, beam, or column showing blemishes
2.1—Location, size
2.2—Type of concrete
2.2.1—Architectural
2.2.2—Structural
3—Effect
3.1—Name
3.1.1—Description
3.1.2—Photographs
4—Causes
4.1—Design of member
4.1.1—Reinforcement (spacing and size)
4.1.2—Width, depth
4.1.3—Configuration
4.2—Forms
4.2.1—Method
4.2.2—Shape
4.2.3—Anchorage
4.2.4—Insulation
4.2.5—Material type, new or used
4.2.6—Form coatings
4.2.7—Texture and finish
4.2.8—Tightness
4.2.9—Structural adequacy
4.3—Construction conditions
4.3.1—Temperature
4.3.2—Wind
4.3.3—Humidity
4.3.4—Precipitation
4.3.5—Placing accessibility
4.3.6—Precautions, covered in 4.5
4.4—Properties of fresh concrete
4.4.1—Proportions
4.4.2—Workability

4.4.3—Grading of aggregate
4.4.4—Slump
4.4.5—Nominal maximum size aggregate
4.4.6—Cohesiveness
4.4.7—Air content
4.4.8—Time of setting
4.5—Placement
4.5.1—Rate
4.5.2—Conditions
4.5.3—Adequacy of equipment
4.6—Consolidation
4.6.1—Frequency
4.6.2—Amplitude
4.6.3—Physical size
4.6.4—Schedule of insertions
4.6.5—Number of vibrators
4.6.6—Depth of penetration
4.6.7—Length of vibration

CHAPTER 8—REFERENCES

8.1—Recommended references

The documents of the various standards-producing organizations referred to in this report are listed below with their serial designation.

American Concrete Institute

ACI 116R	Cement and Concrete Terminology
ACI 303R	Guide to Cast-In-Place Architectural Concrete Practice
ACI 304.1R	Guide for the Use of Prepackaged-Aggregate Concrete for Structural and Mass Concrete Applications
ACI 309R	Guide for Consolidation of Concrete
ACI 309.1R	Behavior of Fresh Concrete During Vibration
ACI 347R	Guide to Formwork for Concrete

American Society for Testing and Materials

ASTM C 33	Specification for Concrete Aggregates

The above publications may be obtained from:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

8.2—Cited references

Backstrom, J. E.; Burrows, R. W.; Mielenz, R. C.; and Wolkodorff, V. E., 1958, “Origin, Evolution and Effects of the Air Void System in Concrete, Part 3—Influence of Water-Cement Ratio and Compaction,” ACI JOURNAL, *Proceedings* V. 55, Sept., pp. 359-375.

International Council for Building Research, 1975, “Tolerances on Blemishes of Concrete,” *CIB Report* No. 24, International Council for Building Research Studies and Documentation, Rotterdam, 8 pp.

Mather, B., 1987, “The Warmer the Concrete the Faster the Cement Hardens,” *Concrete International*, V. 9, No. 8, Aug., pp. 29-33.

Reading, T. J., 1972, “The Bug Hole Problem,” ACI JOURNAL, *Proceedings* V. 69, No. 3, Mar., pp. 165-177.

Samuelson, P., 1970, “Voids in Concrete Surfaces,” ACI JOURNAL, *Proceedings* V. 67, No. 22, Nov., pp. 868-874.

Shilstone, J. M., 1977, “Surface Blemishes in Formed Concrete,” *Proceedings*, RILEM/ASTM/CIB Symposium on Performance Evaluation of External Vertical Surfaces of Buildings (Otaniemi, Espoo, Aug.-Sept.), Technical Research Centre of Finland, Espoo, Finland, pp. 3-7.

Stamenkovic, H., 1973, “Surface Voids Can Be Controlled,” *Concrete Construction*, V. 18, No. 12, Dec., pp. 597-598, 600.

8.3—Bibliography

Fiorato, A. E., 1973, *Geometric Imperfections in Concrete Structures (A Literature Survey)*, National Swedish Institute for Building Research, Stockholm, Sweden.

Harding, M. A., 1995, “Vibrating Concrete in Wall Forms,” *Concrete Construction*, V. 40, No. 2, Feb., pp. 180-184.

Harrell, T. R., and Goswick, G. M., 1987, “Tunnel Concrete—Consolidation Achieved by a Harmonic Blend of Internal and External Vibration,” *Consolidation of Concrete*, SP-96, American Concrete Institute, Farmington Hills, Mich., pp. 102-118.

Holland, T. C.; Husbands, T. B.; Buck, A. D.; and Wong, G. S., 1980, *Concrete Deterioration in Spillway Warm-Water Chute, Raystown Dam. Pennsylvania (Final Report)*, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Structures Lab. WES/MP/SL-80-19; CTIAC-42, 55 pp.

Houston, B. J., 1967, *Methods of Reducing the Size and Number of Voids on Formed Concrete Surfaces*, Report No. TR 6-788, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 36 pp.

Hurd, M. K., 1993, “Patterned Form Liners for Architectural Concrete,” *Concrete Construction*, V. 38, No. 5, May 5, 5 pp.

Kennedy, T. B., 1960, *Investigation of Methods of Finishing Formed Concrete Surfaces*, Report No. TR 6-559, U.S. Army Engineer Waterways Experimental Station, Vicksburg, Miss., 19 pp.

Kenney, A. R., 1984, “Problems and Surface Blemishes in Architectural Cast-in-Place Concrete,” *Concrete International*, V. 6, No. 1, Jan., pp. 50-55.

Kenney, A. R., and Kenney, B. P., 1986, “Problems and Repairs in Tilt-Up Construction,” *Concrete International*, V. 8, No. 6, Jun., pp. 41-50.

King, J. C., 1971, “Special Concretes and Mortars,” *Handbook of Heavy Construction*, 2nd Edition, McGraw-Hill Book Co., New York, pp. 22-1 to 22-17.

Mass, G. R., 1987, “Consolidation of Concrete,” *Lewis H. Tuthill International Symposium on Concrete and Concrete Construction*, SP-104, Gant T. Halvorsen, ed., American Concrete Institute, Farmington Hills, Mich., pp. 185-204.

Reading, T. J., 1985, “Deleterious Affects of Wood Forms on Concrete Surfaces, *Concrete International*, V. 7, No. 11, Nov., pp. 57-62.

Sansalone, M., and Carino, N. J., 1988, “Impact-Echo Method: Detecting Honeycombing, Depth of Surface-Opening Cracks, and Ungrouted Ducts (Final Report),” *Concrete International*, V. 10, No. 4, Apr., pp. 38-46.

Shilstone, J. M., 1979, “Surface Blemishes in Formed Concrete,” *Concrete Construction*, V. 24, No. 11, Nov., pp. 719 and 765.

Smith, John R., 1984, “Architectural Concrete: Defects Demand Discretion,” *Concrete International*, V. 6 No. 1, Jan., pp. 64-66.

Watanaba, T., and Uomoto, T., 1993, “Monitoring Concrete Placing by Infrared Image Analysis,” *Doboku Gakkai Rombun-Hokokushu/Proceedings of the Japan Society of Civil Engineers*, No. 478, Part 50-21, pp. 55-59.