FINAL REPORT

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Examination and Evaluation of ACI 347.3R-13 "Guide to Formed Concrete Surfaces"

by

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PROVIDING THE MEANS TO ADVANCE CONCRETE CONSTRUCTION

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Executive Summary

After ACI 347.3R-13-13, “Guide to Formed Concrete Surfaces,” was published in early 2014, a study was funded to evaluate and examine the Guide. A summary is provided below.

- In a review of ACI 347.3R-13 similar to an ACI document review, the investigators expressed concerns about the mixture of objective and subjective criteria for categorizing formed surfaces, mandatory language used in the Guide, and vague or undefined words or phrases. Complexity and achievability of recommendations in the Guide were also questioned. Chapters 2 through 4 of this report summarize results of the review and Appendix B contains the full review.
- A literature review of information on bugholes—as measured by the surface void ratio (SVR) recommendations in the Guide—provided background information on SVR recommendations, other criteria for assessing and classifying surface appearance, optoelectronic image analysis for measuring SVR, factors affecting the size and frequency of bugholes, and methods for controlling the factors. Results of the review are summarized in Chapter 5 of this report, and Appendix C is an annotated bibliography of the literature reviewed.
- Student researchers in the Middle Tennessee State University (MTSU) Concrete Industry Management (CIM) program made SVR measurements on photos of walls with varied sizes and numbers of bugholes while testing several methods of measurement including the method described in the ACI Guide. They chose three measurement methods for further study on as-built vertical concrete as described in Chapter 6 of this report.
- The MTSU student researchers next built a wall for use in testing different SVR measuring methods and estimating the variability among 2-ft by 2-ft samples randomly chosen on the wall. There were wide variations in SVR for sample-to-sample testing and within-sample testing on the test wall. The data collected enabled development of SVR sampling and measurement protocols for use by student researchers from three other CIM schools.
- Students from the other three CIM schools made SVR measurements, first on photos to develop reproducibility data, then on in-place walls in their geographic area. MTSU CIM students also made SVR measurements on in-place walls in Tennessee.
- Data from the CIM student researchers was supplemented by data obtained from three U.S. commercial testing laboratories.
- Wide variations in SVR for sample-to-sample testing and within-sample testing were again evident. Based on convergence of the running average for multiple measurements, about six to nine samples were needed for the MTSU test wall with an average SVR of about 3%. Need for a similar number of samples was indicated by testing laboratory results on a wall with an average SVR of about 0.4%.

- On a trip to Germany, the principal investigator found that evaluation of SVR on an as-built wall is based on one “representative” sample chosen by the general contractor.
- Results from measurements made by CIM student researchers and testing laboratories indicate that, based on one sample, measurement and sampling error can produce SVRs for a given wall placing it in the worst to best category.
- The literature review produced little evidence that producers’ or contractors’ methods for concrete production or construction can be modified to consistently produce a given SVR due to the number of variables involved.
- This report recommends that requirements for both color, which is subjective, and SVR, which appears to be objective but is subject to sampling and measurement error, be omitted from any recommendations for formed vertical surface appearance.

This report recommends not including ACI 347.3R-13 as part of a bid package and not converting it to a specification.

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CHAPTER 1. INTRODUCTION

ACI 347.3R-13, “Guide to Formed Concrete Surfaces,” was published in early 2014. The Guide defines four formed concrete surface categories (CSCs). The lowest classification is CSC1 (the Guide gives basement walls as an example) and the highest classification is CSC4 (the Guide gives monumental or landmark structures for examples). Factors influencing these categories are as follows:

- Texture at panel joints (four levels) related to fins, offsets, imprints of modular panels, and other effects of formwork components, including facing materials.
- Surface void ratio (four levels) defined as the total area of bugholes in a 2x2-ft square sample expressed as a percentage of the sample area.
- Color uniformity (three levels) described in subjective terms.
- Surface irregularities (four levels) based on Class A through D surfaces as described in ACI 117-10.
- Construction and facing joints (four levels) based on acceptable offsets between adjacent placements and use of chamfer-strip reveals to conceal joints.
- Form facing categories (three levels) related to condition of the form facing prior to concrete placement.

Tables 3.1a through 3.1d in the ACI 347.3R-13 Guide are reproduced in Appendix A of this report. These tables include detailed information concerning the quality levels represented by the concrete surface categories. As stated in ACI 347.3R-13: “The basic procedures for classification were defined using tables from recommendations of the German Concrete Association...”

At the American Society of Concrete Contractors (ASCC) 2012 Annual Convention in Lisle, Illinois, the principal author of ACI 347.3R-13, Rolf Spahr, gave a presentation on the document, followed by a roundtable discussion with ASCC contractors. There was a particularly long discussion concerning surface void ratio recommendations. ASCC members present at the discussion were also concerned about:

- Clarity of the recommended requirements.
- Complexity of the recommended requirements for surface finish.
- Achievability of the recommended requirements by U.S. contractors.

This research report provides information on the concerns mentioned, and also includes data that indicates deficiencies in the suggested sampling and measurement method for surface void ratio (SVR).

CHAPTER 2. CLARITY CONCERNS

One of the first activities for this project was a thorough review of ACI 347.3R-13-13. The review format is similar to an ACI document review, citing specific passages, phrases, or words, then adding comments, requests for clarification, or both. The review included suggestions for either alternative language or deletion of some portions of the document. It also summarized attributes of formed surfaces or forms with regard to whether or not they were measurable and whether or not there was a measuring method and a sampling plan for the measurements as shown in Table 2.1 See Appendix B for the full review.

Concerns raised in the review were as follows:

- Overall evaluation of the surface impression, which is subjective.
- Other criteria such as SVR that are objective.
- Mandatory language usage in an ACI Guide that should be limited to non-mandatory recommendations.
- Vague and undefined words or phrases, or terms not commonly used in the U.S.

2.1 Subjective evaluations

The Introduction to ACI 347.3R-13 states that the Guide: "…provide[s] definitions for the various levels of formed concrete surfaces, and give[s] objective evaluations of them." The second footnote for Table 3.1a, however, contains two important subjective sentences or phrases as indicated in parentheses:

"*The appearance of the formed concrete surface should only be judged in its entirety not by looking at separate criteria only*." and

"*The failure of one agreed criterion according to this guide should not result in the obligation to repair deviations if the overall positive image of the structure or the building is not disturbed.*"

Both of these sentences indicate that objective evaluations can be overruled by subjective evaluations.

Table 3.1b states that for a CU1 classification: "Light and dark color variations are acceptable." And for a CU2 classification: "Gradual light and dark discolorations are acceptable." The implied difference between "color variations" and "discolorations" is subjective. For a CU2 classification it is also recommended that: "Color consistency between adjacent placements and layer lines should be mostly uniform." All three of these sentences indicate that the classifications are based on subjective opinions.

2.2 Objective evaluations

The SVR determination seems to be objective, but is not. Section 3.2 includes the following statement: "The surface void ratio is only required to be determined if the entire impression of the surface does not meet the contract expectation." The "entire impression" is a subjective evaluation, and "contract expectation" is a vague term. The contract expectation is that the contractor will produce an acceptable product that meets the specification requirements. If the specification cites a formed surface category, the primary determinant of acceptance is the subjective determination of the entire impression. If such a subjective evaluation can overrule SVR evaluations, these evaluations are of no value in determining acceptance of part or all of the structure.

2.3 Use of mandatory language

Variations of the word “require” are used in Table 3.1a and in footnotes for Tables 3.1b and 3.1c.of the ACI Guide. And as noted previously, Section 3.2 states: “The surface void ratio is only required to be determined if the entire impression of the surface does not meet the contract expectation.” Section 7.2.1 of the ACI Technical Committee Manual (TCM) states that “ACI guides present committee recommendations for analysis, design, specifying, selection, evaluation, testing, construction, or repair of concrete materials or structures.” A recommendation is not a requirement. Section 7.2.1 of the TCM further states that: “ACI guides are written in nonmandatory language. Mandatory language can be used in nonmandatory-language documents when quoting directly from or referring to provisions in a document that uses mandatory language or is suggesting requirements.” As an example of this, Section 7.6 of ACI 302.1R-15 states: “Curing compounds should meet or exceed the water-retention *requirements* [italics added] of ASTM C309.” Contrary to instructions in the TCM, ACI 347.3R-13 does not use the word “requirements” only when quoting directly from or referring to provisions in a document that uses mandatory language or is suggesting requirements.

The incorrect use of mandatory language in a Guide is not a minor concern. Many specifiers reference ACI Guides in their specifications, even though a disclaimer in every ACI Guide states: “Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.” When the Guides are referenced, contrary to ACI policy, the use of mandatory language can be used to show that the contractor was *required* to carry out tasks not spelled out in the project specifications. Lawyers often don’t distinguish between guides and specifications.

Table 2.1 Summary of Attribute Measurables, Methods, and Sampling Plans

	Measurable		Method		Sampling Plan	
Attribute	No	Yes	No	Yes	No	Yes
Overall impression (Chapter 7)	X		X		X	
✓ Overall impression of surface appearance is the basic acceptance criteria - Normal lighting conditions - Viewed from at least 20 ft. - Viewed form at least 8 weeks after placement						
If overall impression is not satisfactory, the following must be considered:						
Texture, panel joint (Table 3.1b)		X		X^1	X	
✓ Acceptable gaps in adjacent formwork components		X		X^1	X	
✓ Acceptable depth of mortar loss		X		X^1	X	
✓ Acceptable surface offsets of panel joints		X		X^1	X	
✓ Acceptable projections from adjacent surface		X		X^1	X	
✓ Form-facing materials		X		X^1	X	
✓ Imprints of modular panel		X		X^1	X	
Color uniformity (Table 3.1b)						
✓ Light and dark color variations	X		X		X	
✓ Color variations between adjacent placements and layer lines	X		X		X	
✓ Rust and dirt stains and visible pouring layers	X		X		X	
✓ Concrete source materials and form-facing material should be consistent	X		X		X	
Surface irregularities (Table 3.1b)						
✓ ACI 117-10, section 4.8.3: formed surface irregularities		X		X	X	
✓ Maximum gradual deviation over a distance of 5 ft. or abrupt deviation		X		X	X	
✓ Limit deflection of formwork structure		X		X	X	
✓ ACI 117-10, section 4.8.2: formed surfaces over distances of 10 ft.		X		X	X	
Construction and facing joints (Table 3.1b)						
✓ Acceptable offset of surfaces between two adjacent placements		X		X	X	
✓ Use of chamfers strips and reveals		X				X
✓ Coordinate construction joint locations with architectural design.	X		X		X	
✓ Mockup contain all features representative of finished project.		X		X		X
Form-facing categories (Table 3.1c)*						
✓ Holes		X	X		X	
✓ Vibrator burns		X	X		X	
✓ Scratches/dents	X		X		X	
✓ Concrete remnants	X		X		X	
✓ Cement residue	X					
✓ Swelling of facing or fastener or tie holes	X					
✓ Patching		X	X		X	
Surface void ratio (Table 3.1d)						
✓ Void area of pores, percent		X^2	X^3		X	
✓ Maximum void size		X		X^1	X	

X^1 -- no method stated, but it is assumed that a tape measure can be used

x^2 – measurable, but variability is huge

X^3 – the rectangle method described in the document has been found to be insufficiently precise.

* -- subjective attributes to be evaluated prior to each use of the form sheathing.

2.4 Vague and undefined terms

Vague and undefined words or phrases, plus terms not used in the U.S., are a concern because they can result in differing interpretations that cause confusion and possible conflicts during the bidding and acceptance phases of building construction.

For instance, in Chapter 2, *reference area* is defined as a significantly large area of a completed concrete surface serving as a basis of comparison for the acceptance of a surface category of work at a specified location of a given project. There are three problems with this definition:

- A “significantly large area” is a vague, undefined term.
- The definition states that the reference area serves as a basis for comparison for the acceptance of a surface category. But that doesn’t seem correct with respect to the document’s use of the phrase “surface categories,” because the phrase, “reference area,” is not used in Table 3.1a.
- The phrase is used only once in the body of the document. The title of Section 5.2.2 is *Reference area*, and that section states: “The use of an area in an existing building may be used as a reference only and not as a mockup; it is close to impossible to reproduce an area in exact detail. Create a mockup to illustrate the contractor’s ability to reproduce the appearance of the existing structure used as a reference. Construction should conform to the selected reference surfaces and fulfill contract requirements.” This might mean that surface categories CSC1 and CSC2, which don’t require a mockup, can use a reference area from a completed building, but that is not clear.

In Table 3.1a, the description for a CSC1 category is: “Concrete surfaces *in areas with low visibility* or *of limited importance* with regard to formed concrete surface.” Both of the italicized phrases are vague and don’t seem to be the same as the following definition from ACI 347.3R-13 Chapter 2: “area exposed to view—portion of structure that can be observed by the public during normal use.” The two phrases could be based on the number of people likely to view the concrete surface during normal use, on whether or not the people who view it are members of the public, or on environmental conditions during viewing. How does the licensed design professional decide, when marking different surfaces on the drawing?

Table 3.1d implies that contractors know how to, or can be told how to, use construction methods that are sophisticated enough to separate surface void ratios into the stated ranges of 1.2%, 1%, 0.6% and 0.3%. Information cited later in this report indicates that these ranges are not realistic. The “suggested concrete placement practices to yield desired results” are also so vague as to be of little use in producing a surface falling into the stated ranges. The table also implies that contractors know how to, or can be told how to, control maximum bughole size in 1/8-inch diameter increments.

For example, suggested concrete placement practices for an SVR3, includes a statement that: “Adequate vibration should be provided especially at features, openings, and embeds.” Adequate vibration is a vague phrase. Perhaps something more helpful could be added such as a reference to particular sections in other ACI publications. Also: “Concrete mixture consistency is important in achieving reproducible results.” The term “consistency” has two possible meanings in concrete technology. It can refer to slump or slump flow, or it can refer to limited variations in slump, slump flow, or other plastic properties. The latter definition is probably the intent but, if so, which properties need to be consistent, and what range for these properties is considered to be consistent? The vague phraseology makes this suggested concrete placement practice of little value.

Terms not used in the U.S. are found in Section 4.2:" The use of filling nozzles_may be required for placing highly flowable concrete or SCC." Are filling nozzles drop chutes, flexible drop chutes (elephant trunks), or pump discharge hoses? And in 4.2e): "At recesses, reveals, flutes, rebates or other locations…" Are "rebates" the same as "returns (the upper radius of curved precast panels)?"

In Section 5.2.1e), "Incorporate into the mockup building geometries the: reinforcing bar cover, reinforcing bar finish …" What is "reinforcing bar finish?" Does this refer to black steel, epoxy-coated, stainless steel, or galvanized bars? And 5.3f) refers to "alkali streaks." What is an alkali streak? Is this a phrase meaning efflorescence? If not, what does it mean?

CHAPTER 3. COMPLEXITY OF THE RECOMMENDATIONS

Varying quality levels for formed surfaces should be expected when building, for instance, an industrial structure versus a cathedral. It would also be expected that recommendations for construction of a cathedral would be more complex than those for an industrial structure. In the ACI document, however, even “normal” concrete is subject to recommendations nearly as complex as those for the cathedral, as illustrated below.

3.1 Tables describing formed surface categories

As indicated in Appendix A, four tables describe up to four quality levels for surfaces assigned to four different concrete surface finish categories (CSCs). A larger CSC number indicates higher quality.

Table 3.1a describes the following categories:

- CSC1— the basic recommendation for, say, basement walls or for industrial structures,
- CSC2—the normal recommendation for, say, electrical and mechanical rooms where visual appearance is of moderate importance,
- CSC3—a special recommendation for, say, commercial building exteriors where appearance is important, and
- CSC4—also a special recommendation for, say, monumental or landmark structures, where exposed concrete is a prominent feature of the completed structure.

Table 3.1b describes the following visible effects on as-cast formed surfaces:

- Texture, panel-joint effects ranging from T1, T2, T3, and T4. As indicated in Table 3.1b, these are based on allowable size of form offsets, fins, and other effects found at panel joints.
- Color uniformity ranging from CU1, CU2, and CU3. As indicated in Table 3.1b, these quality recommendations are based on the presence of layer lines, light and dark color variations within a single placement or between adjacent placements, and dirt or rust stains.
- Surface irregularities ranging from SI1, SI2, SI3, and SI4. As indicated in Table 3.1b, these are based on formed surface tolerances in ACI 117-10 that limit abrupt and gradual deviations from plane surfaces.
- Construction and facing joints ranging from CJ1, through CJ2, CJ3, and CJ4. These are based on allowable size of offsets at construction joints between adjacent placements, and on recommendations for chamfer strips or reveals at construction joints.

Table 3.1c describes form-facing categories FC1, FC2, and FC3. These categories are based on the condition of the form facing prior to each concrete placement and whether or not form facing conditions such as holes, vibrator burns, scratches/dents, and cement remnants or residue are acceptable.

Table 3.1d describes concrete surface void ratio (SVR) on as-cast formed surfaces ranging from SVR1, SVR2, SVR3, and SVR4.

To assess the impact of these quality recommendations being included in construction documents, consider how a typical formed concrete surface would compare with one having the recommended CSC2 quality level. This is described as normal concrete, "concrete surfaces where visual appearance is of moderate importance" and includes possible examples of industrial structures, electrical and mechanical rooms, and stairwells. Here are the requirements:

3.2 Example of quality level where visual appearance is of moderate importance

- Texture (T2)
    - Acceptable gaps in adjacent formwork components ≤ 1/2 in.
    - Acceptable depth of mortar loss ≤ 3/8 in.
    - Acceptable surface offsets of panel joints up to 1/2 in. (ACI 117-10, Section 4.8.3, Class C).
    - Allowable projections 1/2 in. from adjacent surface.
    - Form-facing material examples: Class BBOES plywood, MDO plywood.
    - Imprints of modular panel frames are acceptable.

- Surface void ratio (SVR2 or SVR1)
  Void area of pores of surface occurring within a 24 x 24 in. square test area
    - Void area not to exceed 1.2 percent of test area.
    - Exclude voids with an average diameter less than 3/32 in.
    - Maximum *average* void size (*diameter*) of ¾ in. [italics added]

- Color uniformity (CU1)
    - Light and dark color variations are acceptable.
    - Color variations between adjacent placements and layer lines are acceptable.
    - Rust and dirt stains are acceptable.

- Surface irregularities (SI2)
  ACI 117-10, Section 4.8.3, Class C-Surface.
    - Maximum gradual deviation over a distance of 5 ft (152 cm), or abrupt deviation is 1/2 in.
    - Limit deflection of formwork structure to *L*/360.
    - ACI 117-10, Section 4.8.2 does not apply

- Construction and facing joint (CJ2)
    - Acceptable offset of surfaces between two adjacent placements ≤ 1/2 in. (13 mm).
    - The use of chamfer strips or similar reveals are recommended at construction joints.

- Form-facing category (FC1)
    - Holes, greater than 3/16 in. – plug or disk covers are acceptable.
    - Holes, 3/16 in or less – acceptable.
    - Vibrator burns – acceptable.
    - Scratches/dents – acceptable.
    - Concrete remnants – acceptable.
    - Swelling of facing at fastener or tie holes – acceptable.
    - Patching – acceptable.

ACI 347.3R-13 indicates that these recommendations for “normal” requirements, with standard formwork and placement practices, should require no special effort and have an average relative cost. But are these complex recommendations needed for the production of “normal” formed concrete surfaces where visual appearance is of moderate importance? The level of detail given seems incommensurate for all but architectural concrete surfaces (**Suprenant 2014**).

CHAPTER 4. ACHIEVABILITY OF CONCRETE SURFACE FINISHES

Two criteria—surface void ratio and color uniformity--used in establishing the four formed concrete surface categories (CSCs) were of particular concern to concrete contractors. Surface void ratio is a measure of the size and number of bugholes (also called blow holes or surface air voids). The causes and factors affecting bughole formation have been studied for at least 50 years but, surprisingly, there has been little progress made in understanding the causes. Nor do we know as much as we need to about changes in structural design, materials, forming, and construction methods that minimize the size and number of bugholes, as indicated in results of a literature search (Appendix C) that was a part of this research. The same can be said about color uniformity.

4.1 Risk management

In preparing a bid for structures requiring formed surface categories as described above, estimators would have little background information on which to base their cost estimates. They have to prepare a bid to ensure that owners get what they paid for and contractors get paid for their work. Field personnel, in turn, would need to determine the appropriate formwork and form release agents, concrete mixture properties, and placing and consolidating techniques in an attempt to achieve the surface category described. A two-phase bid would be preferable when CSCs are specified. A basic bid would be supplemented by an allowance for additional work needed if color or SVR were not satisfactory.

4.2 Achievability as a bidding and production problem

Because the four concrete surface categories are those from a German document and are based on European contractors' experience, U.S. contractors have no precedent for bidding on or producing the desired product. Thus, determining the achievability of a specific concrete surface category while using U.S. construction methods is unknown. Ability to achieve the surface void ratio limits included in Table 3.1d was of special concern to ASCC contractors because no data were referenced as a basis for setting the four SVR levels in the table.

Further, if deviations from the expected SVR are pointed out, ACI 347.3R-13 recommends basing the SVR on one sample from the building unit under consideration, but with no details given as to how the sample is chosen. There is also no ASTM standard for the SVR measurement method. Based on data developed in this report, the method described in ACI 347.3R-13, does not adequately discriminate among the four SVR levels.

There are similar concerns about the recommendations for color uniformity. More data on repeatability and reproducibility are needed to show that any classifications for these two properties are clearly differentiated. The data should also be used to clearly indicate how the concrete producer and concrete contractor can achieve quality levels suggested for these two properties.

CHAPTER 5. ANNOTATED LITERATURE REVIEW ON BUGHOLES

A literature review was conducted to evaluate the level to which the following subjects had been covered in past publications and research programs:

1. Additional background on the German Concrete Association's (DBV) (Merkblatt Sichtbeton Deutscher Beton-und Bautechnik-Verein e.V. 2004), the document with tables used in the formed-surface classification system in ACI 347.3R-13.
2. Formed surface appearance criteria and classification systems that predate or post-date ACI 347.3R-13.
3. Optoelectronic image analysis methods for measuring color scale and SVR.
4. Factors affecting the size and frequency (number per unit area) of bugholes including concreting materials, mixture proportions, formwork and form release agents, construction methods, and environmental conditions.
5. Methods suggested for limiting size and frequency of bugholes by controlling the factors listed in Item 4.

All references in the review are annotated to further describe the findings and, in the case of research, the methods and materials used. In the following discussion, references are cited by author and year published, with two works in one year designated as (a), (b), and so on.

5.1 Background on DBV Merkblatt Sichtbeton Deutscher Benton-und Bautechnik-Verein e.V. 2004

We could not obtain a copy of the original document, but descriptions of it from several sources provide insight as to the intent and content. **Litzner and Goldhammer (2005)** indicate that the 2004 version was intended for use with architectural concrete as evidenced by the following quotes, [italics added]:

"…information [in the Guide] is based on practical experience that was gained in recent times with *prestigious structures made of exposed concrete*."

"…it aims to promote the use of exposed concrete as *a means of expression in modern architecture.*"

"…*four architectural concrete classes*, SB 1 to SB 4 are defined…"

Hillemeier et al (2005) included a summary of the 2004 version [Exposed Concrete Guide to Good Practice 2004] as follows:

This guide compares exposed concrete deficiencies [including surface porosity] with respect to the current state of the art, as:

- either avoidable or partially avoidable, and
- not (yet) avoidable.

The quality requirements with respect to porosity are shown in the following table.

Tab.2: Detailed information on the quality criterion "porosity"

Porosity class	P1	P2	P3	P4
Maximum pore fraction[1)] in mm^2	3000	2250	1500	750
Maximum pore fraction with respect to a test surface 500 x 500 mm^2	1.2 %	0.90 %	0.60 %	0.30 %
1) Pore diameter 2 < d < 15 mm				

The following quote indicates that compliance with porosity classes P1 through P4 were not reliably achievable in 2005 when the paper was published:

"…requirements are applied to exposed concrete that, according to the current state of concrete technology, are not achievable in a technically reliable manner. These requirements include:

- Uniform colour shade of all visible surfaces on the structure
- Visible surfaces without pores
- Compliance of the pore area fractions with porosity classes P1 to P4
- Uniform pore size and distribution within an individual area and in all visible surfaces on the structure…"

"Deviations from these are regarded as deficiencies whose root cause lies in insufficient knowledge of interfacial interactions between fresh concrete, the type of release agent and the organic polymer coatings on non-absorbent formwork surfaces."

Research using optoelectronic image analysis is cited indicating that widely differing porosities result from the use of formwork panels with one surface class-e.g. phenolic resins—and the same reference concrete. The authors state that:
"…this means that, depending on the selected material of the formwork facing, it is possible to produce exposed concretes with three porosity classes (P2 to P4) from the same concrete mix"

Vikan (2007) reproduced three classification tables from the 2004 German publication in a state-of-the-art report on Quality of Concrete Surfaces. It is interesting to note that the descriptions for the concrete classes were as follows (ACI 347.3R-13 class in parentheses):

- SB 1 (CSC1) Concrete with insignificant demands
- SB 2 (CSC2) Concrete with normal demands
- SB 3 (CSC3) Concrete with high demands
- SB 4 (CSC4) Concrete with especially high demands

Examples given for each class were similar to those in ACI 347.3R-13, but the phrase "insignificant demands" would seem to indicate no need to limit the SVR to 1.2%, as will be discussed later. In contrast to the report by **Hillemeier et al (2005)**, which lists the four SVR values as maximums, Vikan reports each as "*about* 1.2%, 0.9%, 0.6%, and 0.3%."

The most recent version of the German report **(DBV Merkblatt Sichbeton Deutscher Beton- und Bautechnik-Verein e.V, June 2015)** describes the classes slightly differently, as low requirements, normal requirements, and two classes of special requirements, and also lists the SVR values for each surface class as approximate values.

With respect to the SVR values in the German reports, we have asked ACI Committee 347 why they used "not-to-exceed" class divisions of 1.2%, 1.0%, 0.6%, and 0.3%. Based on our research described later, and on comments in other German publications, sampling and measurement errors can result in one surface falling into any one of three SVR categories. The difference between 1.2% and 1.0% would seem to not be statistically significant.

5.2 Formed surface appearance criteria and classification systems that predate or postdate ACI 347.3R-13

Houston (1967) was one of the first researchers to attempt a quantitative evaluation of bugholes in laboratory tests. Surface voids were counted and grouped according to the following sizes:

a. 1/8- to 1/4-in. dia. b. 1/2- to 1-in. dia. c. Over 1-in. dia.

Because larger voids create a more unsightly appearance than smaller ones, a weighting system based on surface area of the voids was used in a statistical analysis of lab tests. The a.-group voids had a weighting of 1, with b.-group having a weighting of 6 and c.-group a weighting of 23. The factors of 1, 6, and 23 were multiplied by the number of voids in the respective size groups and results were summed to obtain weighted totals. Conclusions were based on tests with relatively stiff concrete (normal workability: 2-1/2-in., low workability 1-3/4-in., and high workability: 4-1/2-in.), SAE oil used as a form release, and without modern form facings. So they're interesting but not applicable today except for the sloping surface problem.

- High air contents and high and low water contents *may* increase incidence of surface voids, but results were not [statistically] conclusive.
- Voids on vertical surfaces can be reduced to an acceptable level by proper and sufficient vibration, but this was not necessarily true for sloping form surfaces.
- Smooth, slick form coatings may be beneficial in reducing voids, but their influence is small compared to other factors.
- Parting oils [barrier-type form release agents] had a limited value in reducing surface voids.

Thompson (1969) presented an early synopsis of results of an investigation into the occurrence of blowholes and the methods of reducing or eliminating them. He recommended a standard of reference that could form a basis for specifications. Ideally, the standard would be a series of full-size sections of the structure under discussion. If this is impractical, the author suggests that smaller panels may be adequate, and failing this, one-foot-square full-sized photos may be used. The article included a set of ten such photos in small scale, and the author stated that the use of such photos has been adopted in preference to a number of more sophisticated methods based on the measurement of diameters and areas of holes [See Houston, B.J. in Appendix C]. The author also claims that using the photos is much simpler and is generally equally or more satisfactory than other methods. Thompson is critical of architects who want bughole-free formed concrete surfaces, as noted in the following quote (italics added):

"Blowholes are endemic in concrete, and a wise architect will avoid specifying finishes that are free of blowholes, unless he allows the holes to be filled in after the forms are removed. *Often, the formation of a moderate number of holes is unobjectionable, and the architect may even welcome their formation as being characteristic of the material with which he is working. Often, too, they are far less noticeable than the so-called 'making good' [repair] which disfigures much exposed concrete."*

Samuelsson (1970) developed an objective grading system for vibrated surfaces based upon the diameter of surface voids measured on square columns, with three samples chosen on each of the four column surfaces as shown.

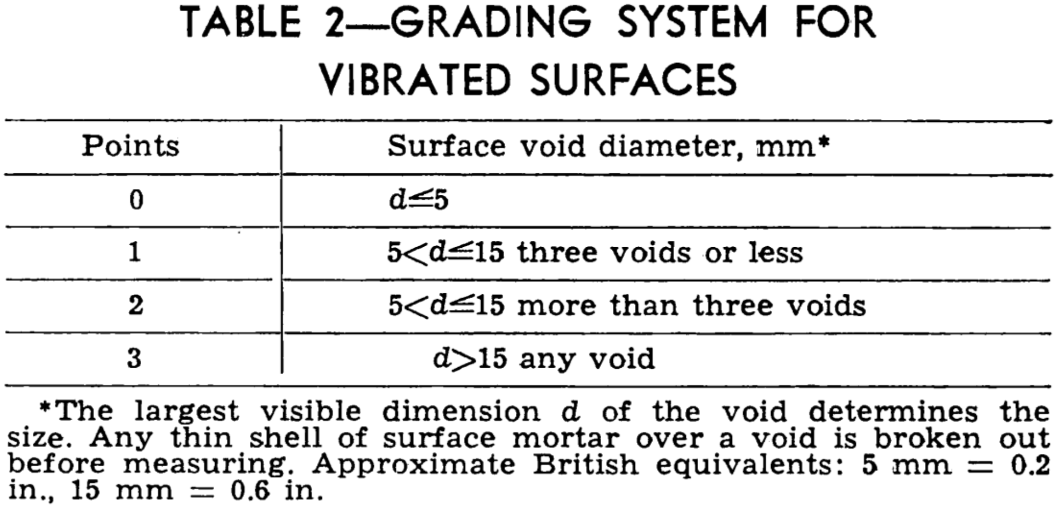


TABLE 2—GRADING SYSTEM FOR VIBRATED SURFACES

Points	Surface void diameter, mm*
0	$d \leq 5$
1	$5 < d \leq 15$ three voids or less
2	$5 < d \leq 15$ more than three voids
3	$d > 15$ any void

*The largest visible dimension d of the void determines the size. Any thin shell of surface mortar over a void is broken out before measuring. Approximate British equivalents: 5 mm = 0.2 in., 15 mm = 0.6 in.

A test surface receiving 0 or 1 points was given a passing grade, so a passing grade for one whole side of a column (three test surfaces) could not exceed 3, and the corresponding passing grade for the whole columns was 12. A total of 100 columns were cast with controlled variables that included concrete slump, lift thicknesses, vibration methods, and several other variables. Results for some of the columns are shown in the table in Appendix C. Seven columns cast under identical conditions received grades of 6, 10, 12, 14, 17, 21, and 23 (av. about 15 and standard deviation about 6). That was the basis for the following statement in the report summary (italics added):

"Great care must therefore be taken in the interpretation of data from a few comparisons. *The wide distribution in the laboratory tests explain why, in actual practice, one succeeds one time and fails another time when the same procedures are used.*"

CIB Report No. 24 (1973) included a subjective classification method for off-the-form concrete surfaces based on two seven-photo sets showing varying size and frequency of blow holes and color differences (Class 7 had the highest and Class 1 the lowest incidence of blow holes). The report divided surfaces into four classes: Rough (no requirements); Ordinary (appearance is a minor factor but still of some importance); Elaborate (Definite requirements for visual appearance); and Special (calling for the highest standards of appearance). It also divided blow holes into two groups: 1. Voids grouped in small areas, and 2. Voids distributed over the entire formed surface. The report emphasizes *not* considering absolute values but, instead, variations over the whole surface. Thus, even for a Special class, a surface is acceptable if it matches Class 6 photos provided that the blowholes are uniformly distributed. The report also states that numerical values should be treated like strength test results, allowing some variance from “perfect,” e.g 95% for Special class, 80% for Elaborate class, and 70% for Ordinary class. Bissonnette et al, 2016 cited CIB 24 but stated: “…it is difficult to evaluate blowholes over an entire surface by comparing with a small-size comparator.” A seven-level scale is placed on the concrete surface and an inspector views it from 3 to 10 meters depending on the standard used. To identify the blowhole level, the observer compares the scale with the concrete surface. “*This method is subjective and does not yield important information like the percentage of surface exhibiting voids, the estimated number of holes, and the hole size range.”* (Italics added).

Anon., (a) (1990) Proposes a six-point classification from CCS 1 (smallest and fewest bugholes) to CCS-6 (largest and most bugholes), with actual size unretouched photos that illustrate the six classes. Recommends differing proprietary form release agents and film thicknesses for each class. Increasing film thickness results in more and larger bugholes.

Hurd (1999) includes discussions of fins, offsets, bugholes, tie holes, and honeycomb. It includes photos of concrete surfaces showing a range of bughole size and frequency in as-cast surfaces. Also shows photos taken from about 15 to 20 ft and close-ups of the same areas. It is a photo classification system but, as stated in ACI 347.3R-13, simply illustrates varying appearance expectations.

Formwork for Concrete, Part 1 (AS 3610.1—2010), describes five classes of surface finish. Table 3.2.1 in that Standard describes applicability of the most demanding surface classes (1 through 3) for which visual quality is important. These are described as follows: Class 1 is subject to close scrutiny, Class 2 requires uniform quality and texture over large areas, and Class 3 requires good visual quality when viewed as a whole. For classes 4 and 5, visual quality is considered not to be important. A note indicates:

- Class 1 is recommended only for use in very special features of buildings of a monumental nature.
- Class1 *shall not be specified for whole elevations or extended surface areas* (italics added).

Table 3.3.2 in Appendix A of the Standard refers to three photo sets of surfaces exhibiting differing blowhole sizes and distribution. These are used as indicators of the requirements for the permissible size and frequency of blowholes for Classes 1-3. For each class there is a general photograph at scale 1:5 that gives a clear idea of expected variation in blowhole size and frequency. A close-up photograph at scale 1:1 shows an area that is representative of the general photograph. Blowhole size and frequency is evaluated by comparison of the completed work with the relevant photographs for the Classes 1-3. The 1:1 scale photograph is held against the surface and viewed from a distance not less than the greater of 6 m or the closest distance from which the subject area will normally be observed when the project is completed. A note in the Standard indicates that printed photographs in Appendix A should not be photocopied or printed from a downloaded copy of AS 3610.1—2010 because they will not produce results consistent with those from an original printed photograph and should not be used for evaluation purposes.

Specifications for Structural Concrete (ACI 301-10) was the first document to establish in mandatory language, and mostly measurable and objective requirements, three different as-cast formed-finishes. They were not changed in ACI 301-16 and are described, as follows:

Surface finish-1.0 (SF-1.0):

(a) No formwork facing material is specified
(b) Patch voids larger than 1-1/2 in. wide or 1/2 in. deep
(c) Remove projections larger than 1 in.
(d) Tie holes need not be patched
(e) Surface tolerance Class D as specified in ACI 117
(f) Mockup not required

Surface finish-2.0 (SF-2.0):

(a) Patch voids larger than 3/4 in. wide or 1/2 in. deep
(b) Remove projections larger than 1/4 in.
(c) Patch tie holes
(d) Surface tolerance Class B as specified in ACI 117
(e) Unless otherwise specified, provide mockup of concrete surface appearance and texture

Surface finish-3.0 (SF-3.0):

(a) Patch voids larger than 3/4 in. wide or 1/2 in. deep
(b) Remove projections larger than 1/8 in.
(c) Patch tie holes
(d) Surface tolerance Class A as specified in ACI 117
(e) Provide mockup of concrete surface appearance and texture

Note that there are no references to bughole frequency (number of bugholes/unit area), to bughole area as a percentage of a sample area (SVR), or to color uniformity. Nor is there any reference to uniform appearance criteria. However, the SF-3.0 and possibly SF-2 finishes require a mock-up, and the mock-up comparison with the as-built building components is subjective.

Klovas, Albertas, and Dauksys, Mindaugas (2013) measured blowholes on concrete surfaces and classified the surfaces in accordance with visual appearance based on:

- Reference photos in CIB Report No. 24,
- The largest dimension of the blowholes as indicated in GOST 13015.0-83 and,

- The authors' proposed optoelectronic image scanning method using "ImageJ" freeware, which permits calculating a ratio between blowhole area and the total area of the scanned image [SVR].

Three different concretes were studied: BA1, BA7 and BA8. Mix proportions, and details of five different formworks were used are shown in Appendix C. The following parameters for [SVR] were calculated: mean value, dispersion, standard deviation, and the coefficient of variation. Also, maximum and minimum values of experimental results are given. Intervals of the experimental results are provided for each specimen with the biggest possible interval.

Table 4 from the article shows how concrete surfaces are evaluated for blemishes [blowholes] by CIB 24 for four different surface classes.

Table 4. Consideration of the blemishes

Blemishes considered	Classes			
	Special	Elaborate	Ordinary	Rough
Distributed holes	0–2	2–4	4–6	No requirement

GOST requirements and explanatory information are as follows:

Table 5. Requirements for the concrete surface quality by GOST 13015.0-83

Categoryof concrete surface	Diameter or the biggest dimension of the blemish	Dimensions of the local rises and cavities	Wreckage depth of the edge	Total length of the wreckages
	Data, mm			
A1	Very smooth surface (reference)		2	20
A2	1	1	5	50
A3	4	2	5	50
A4	10	1	5	50
A5	No require.	3	10	100
A6	15	5	10	100
A7	20	No require.	20	No require

Note that:

- Class A2 concrete surfaces allow one blowhole with a diameter or largest dimension of 2 mm, both per m^2;
- Class A3 concrete surfaces allow one blowhole with a diameter or largest dimension of 6 mm, both per m^2;
- Class A4 concrete surfaces allow one blowhole with a diameter or largest dimension of 15 mm, both per m^2
  .

For image analysis, photos of the concrete surfaces were at about a 30 cm distance and imported into the ImageJ program. Methodology for this and the ensuing analysis is explained. Based on results of the research, Table 8 shows a comparison of how the test surfaces would have been categorized in accordance with GOST, CIB 24, and [SVR] based on ImageJ analysis.

Table 8. Combined concrete category diversification

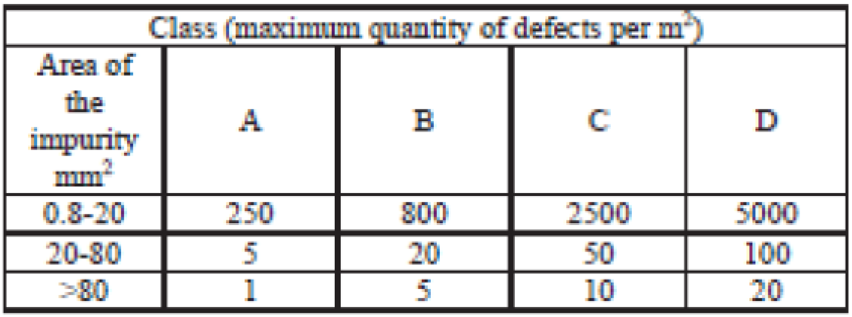
According to methods	Class of the concrete			
	Special	Elaborate	Ordinary	Rough
GOST 13015.0-83, categories	A1 – A2	A3 – A4	A5 – A6	A7 >
CIB Report No. 24. marks	0 – 2	2 – 4	4 – 6	No req.
ImageJ, bugholes area, %	0 – 0.1	0.1 – 2	2 – 4	13 >

Note that for the ordinary class, which would correspond to Class CSC2, the SVR range is 2% to 4%, which is much less restrictive than the 1.0% value permitted by ACI 347.3R-13. The authors recommend using SVR as measured by the ImageJ approach to classify surfaces more precisely and with less ambiguity.

Klovas, Albertas, and Dauksys, Mindaugas (2014) made specimens using two concretes with flow values of 525 mm (vibration needed) and 720 mm (vibration not needed), but details on the specimen shape and size and consolidation methods are not given in this paper.

Detailed descriptions are given for the method by which formed surfaces were analyzed using ImageJ software. The surface quality was determined using the Nordic Concrete Federation system shown in Table 4.

Table 4. Concrete quality classes of surface

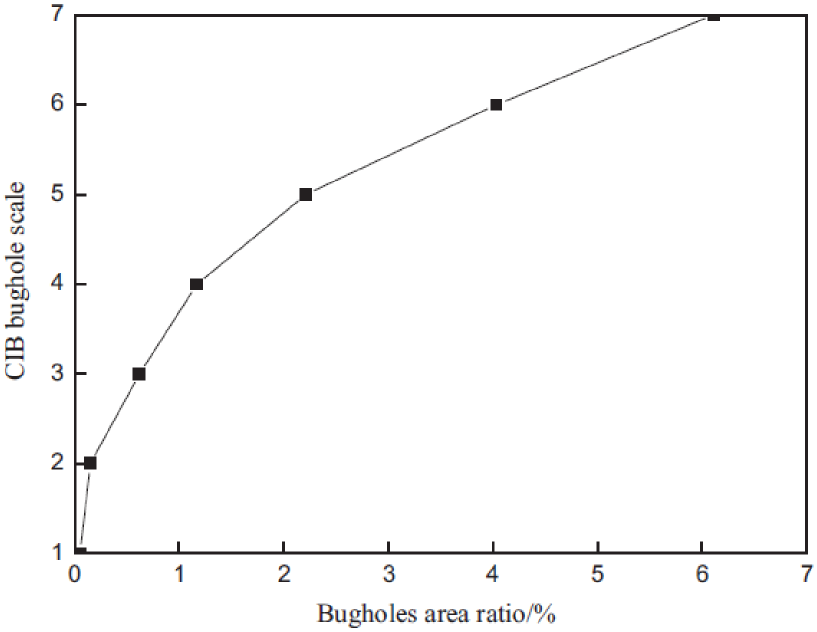


	Class (maximum quantity of defects per m^2)			
Area of the impurity mm^2	A	B	C	D
0.8-20	250	800	2500	5000
20-80	5	20	50	100
>80	1	5	10	20

Of the two concretes tested, the low-flow concrete containing a lower cement content and only a superplasticizer met Class D requirements, and the higher flow concrete which contained a higher cement content and a different superplasticizer plus viscosity modifying and anti-foaming admixtures met Class C requirements.

The authors concluded that ImageJ analysis would be more useful if it provided not only the total area of blowholes, but the largest blowhole dimensions.
The use of more fine particles (higher cement content), and viscosity modifying and anti-foaming admixtures could have determined the surface quality differences between the two concretes.

Liu and Yang (2017) established a method for detecting bugholes on concrete surfaces using image analysis. A relationship between the CIB scale and the area ratio of bughole is established, as shown below.



This relationship is similar to ones published by **Lemaire et al (2005)** and **Silva et al (2011)**. The authors propose recommended requirements for bughole classification that include a maximum diameter. Their digital image method requires a 40 cm focus distance for a detection accuracy of 0.1 mm. For large-size concrete members, the focus distance can be controlled at 50–200 mm, and a sufficient number of photographs must be taken for analysis to ensure the representativeness of the experimental results.

Ozkul and Ismail (2011), Suggested design of a theoretical, but not yet operational, device for measuring bugholes based on how much pressurized gas is allowed to escape from a container with a skirt that crosses the bugholes. Only bugholes crossed by the skirt, with some area inside and outside the skirt are measured. *Simulation* of the device operation was done by overlaying a skirt pattern over a reference of photo concrete surfaces from CIB 24 several times, then measuring the lengths in mm of bughole edges that appear as dark patches covered along the skirt channel. The average length is related to the seven surfaces used as reference samples in CIB 24.

It is interesting to note the following passage regarding different methods for reducing bugholes:

> “Although the methods mentioned above are effective in reducing the number of bugholes, none of the methods are really expected to get rid of bugholes problem completely. In most cases, reducing the surface void area contributed by the bugholes to 1% is considered a successful goal in bugholes reduction.” This one of the few papers that defines “success” in reducing SVR.

Ramsburg, Paul (2004) studied the effects on bughole formation of form materials and release agents for precast members made with SCC. The grading system was based on bughole size, number, and areas of concentrated bugholes (rash).

PRODUCT APPEARANCE	
0	SMOOTH DEFFECT FREE SURFACE SOME MINOR PINHOLES (-1/16")
1	MINOR PINHOLES (-1/16") SOME AREAS OF SMALL BUGHOLES (1/8")
2	MANY SMALL BUGHOLES (1/8") SOME LARGE BUGHOLES (+1/2") MINOR SPOTS OF RASH
3	MANY LARGE BUGHOLES (+1/2") LARGE AREAS OF RASH

FORM CONDITIONS	
0	SMOOTH DEFFECT FREE SURFACE
	NO CONCRETE BUILDUP
	RELEASE AGENT APPLIED LIGHTLY AND EXCESS WIPED AWAY
1	MOSTLY SMOOTH SURFACE MINIMAL ISOLATED DEFFECTS
	ISOLATED AREAS OF LIGHT CONCRETE BUILDUP
	RELEASE AGENT APPLIED LIGHTLY WITH SOME AREAS OF EXCESS
2	SEMI-SMOOTH SURFACE WITH PATCHES OF PITS AND SCORING
	LARGE PATCHES OF CONCRETE BUILDUP
	MODERATE APPLICATION OF RELEASE AGENT WITH AREAS OF
3	ROUGH SURFACE WITH DEFFECT AND RUST PITTING
	CONCRETE BUILDUP AT +1/16" IN AREAS
	RELEASE AGENT APPLIED HEAVILY - DRIPPING AND POOLING

Silva and Stemberk (2013) developed a rather complex expert system that classifies the surface finish of self-compacting (SCC) precast elements. The paper acknowledges that production of SCC is more difficult than that for conventional concrete because more parameters have to be considered. The expert system is comprised of an image analysis tool and a fuzzy logic-based classification tool. The system takes into account not only surface void ratio, but also the maximum bughole diameter and a bughole size distribution curve. The system output is a classification scale value, $C_{S,}$ ranging from 1 (defect free) to 5 (patching, changes in concrete mixture, or both are required). Tests were conducted on laboratory-made samples to illustrate the effects of several parameters on C values, production costs, and surface appearance with respect to bugholes.

Current methods for evaluating precast/prestressed concrete members are simple and direct. **Freedman (2007)** states that if surface air holes are of a reasonable size—1/8 to 1/4 in. –it is recommended that they that they be accepted as part of the texture. Filling and sack rubbing is expensive and may cause color differences. Samples of the mockup panel should be used to establish acceptable air void size, frequency, and distribution.

The quality manual for **NPCA (2015)** considers formed surfaces to be satisfactory if they are relatively free of bugholes, unless the surfaces are required by design to be finished. The manual states that a minor number of voids on the surface is quite normal. Filling of these voids is done for cosmetic purposes and usually only when required by specifications. Post-pour inspections are used to document excessive bugholes. Defects not impairing the functional use or expected life of a precast product are considered minor defects that can be repaired by any method that does not impair the product. Repairs of minor defects are essentially cosmetic, (e.g., the product would behave as intended without the repairs).

As indicated in this portion of the literature review, most of the proposed classification systems are subjective to some degree with respect to bugholes and color uniformity, with the ACI 301-16 system being the least subjective overall.

5.3 Optoelectronic image analysis methods for measuring color scale and SVR

Optoelectronic image analysis using ImageJ freeware appeared in the year 2005 as a faster and presumably more precise way of measuring bughole areas and grayscale variations. Many of the bughole measurements on laboratory-produced specimens were expressed as surface void ratios (SVR), which enabled comparisons with the Table 3.1d SVR limits in ACI 347.3R-13. Klovas and his coinvestigators published several papers dealing with the effects of variables including form facing and form release type and amount, concrete materials and proportions, and consolidation methods.

Lemaire, Gruillaume et al (2005) pointed to conflicts between owners, architects, and general contractors regarding the extent and quantity of bugholes because the CIB Report 24, AFNOR P18-503 standard in France, and the NBN B 21-601standard in Belgium involved subjective judgments. The authors used ImageJ analysis of photos to more objectively analyze both differences in color and size and frequency of bugholes. Photos were taken close enough to distinguish detail of about one square millimeter. A “large number of zones” were measured for color comparisons [many samples]. Images of photos illustrating the seven surface classes in CIB 24 were analyzed by determining the number of bugholes/m^2 and bughole area as a percent of total area [equivalent to SVR in ACI 347.3R-13]. Fig. 13, below, indicates that CIB Classes greater than 3 have SVRs exceeding the maximum allowable value of 1.2% for an SVR1 in ACI 347.3R-13. This would place them in the CSS1 category which applies to concrete surfaces in areas with low visibility or of limited importance with regard to formed concrete surface requirements, used or covered with subsequent finish materials.

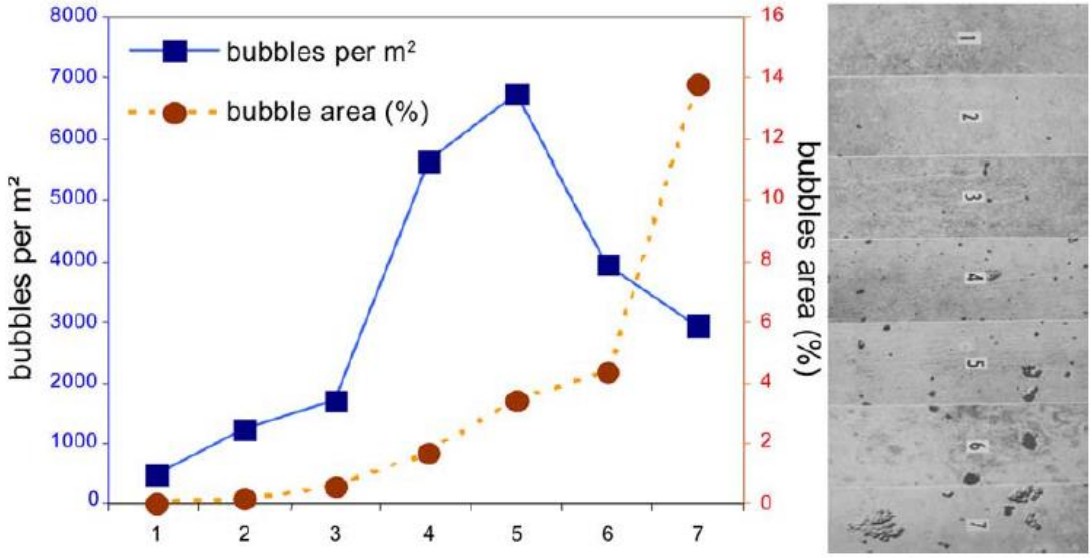
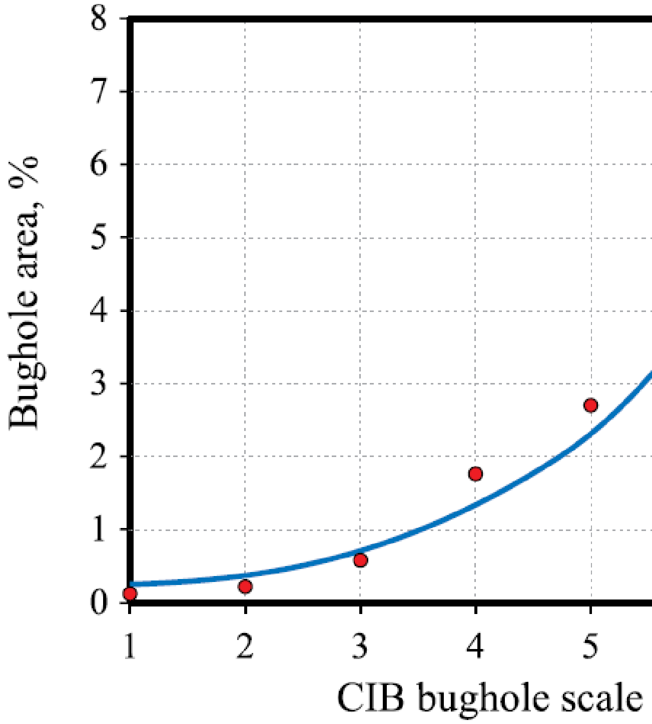


Fig. 13. Bubble board [2] and its characteristics measured by image analysis.

Silva et al (2011) used an image-processing method to measure the area of bugholes on the formed surfaces of precast test panels made in the laboratory with self-consolidating concrete. Their experimental program studied the effects on SCC mixes of:

- Mortar content by volume,
- Total volume of dusty aggregates,
- Ratio of water to total volume of dusty material,
- Water-cement ratio, and
- Dosage of high-range water-reducing admixture

with two different release agents used on laminated plywood forms. Test panels were made with six differing concretes and, to simulate precast concrete plant production conditions, the SCC was placed from a height of 1 m at a single point in the mold to allow the concrete to flow from one end to the other. No vibration was applied. Surfaces of the hardened concrete were analyzed using the image-processing method to create a high-contrast image that highlighted the outlines of bugholes. The projected area of bugholes on the surface was then calculated and expressed as a ratio of void area to the total test area (900 x 250 mm) analyzed. The imaging method was also used to analyze the seven reference photos used for classification in CIB Report No. 24. The results of this are shown below.



The results of this comparison of SVR to the CIB bughole scale are similar to Lemaire's findings. The authors concluded that the image analysis method they used allowed a more objective evaluation of results when compared to the CIB bughole scale.

Klovas, Albertas, et al (2013) Summarized factors affecting surface quality of concrete and presented data on the effects of excessive form release agents on five differing horizontal form surfaces. Experimental details are in Appendix C. ImageJ data indicated that wood covered with rubber formwork produced the most porous surface because it did not absorb the excess form release agent, and sawn timber formwork produced the least porous surface because it absorbed the excess form release agent.

Klovas, Albertas, and Dauksys, Mindaugas, (November 2013) Used ImageJ analysis to study concrete surface quality changes caused by use of different form release agent applications. Concrete surface blemishes [bugholes] were evaluated using a combined method described in CIB Report No. 24 and GOST 13015.0-83 Two different concrete compositions were used: BA1 (low fluidity [525 mm flow], vibration is needed) and BA8 (high fluidity [720 mm flow], vibration is not needed). Three castings were made with each of four differing form facings on mold soffits for horizontal specimens, and one vertical form with facing made of wood impregnated with polymeric oil. Water emulsion based form release agent was used with differing applications (normal and excessive). Some of the data seems to be from previous work done by Klovas, Dauksys, and Linas. The high flow mixtures resulted in fewer bugholes on the horizontal specimen soffits than were noted in the previous work. For CIB Report 24 classes 1, 2, and 3, ImageJ analysis of the vertical form faces indicated bughole area percentages [SVR] of 0% –0.1%; 0.1%-0.3%; and 0.3%-0.5%, respectively.

Klovas, Albertas, and Dauksys, Mindaugas (2015) provided data for fresh concrete properties of superplasticized concretes made with varying amounts of anti-foaming, viscosity modifying, and air-entraining admixtures. The anti-foaming and viscosity modifying admixtures were not useful in reducing the entrapped air content of concrete made with the superplasticizers. No measurements of surface quality were made, but the authors stressed the importance of concrete yield stress in determining risk of blowholes.

Klovas, Albertas (2016) includes a review of different methods for concrete surface quality evaluation. He draws conclusions regarding the effects of concrete rheological properties on formed surface quality but [because it's a summary] with no experimental data connecting the rheological properties with surface quality. Two conclusions, paraphrased, are of interest:

1. On the basis of a systematic analysis of scholarly literature there is lack of scientific information on modifications in concrete mixtures needed to obtain high quality surfaces. Most of the widely available surface quality evaluation methods are actually based on subjective opinion which is not reliable when classifying surfaces according to their quality.
2. The image analysis method (software *BetongGUI 2.0*) easily allows measurement of the quantity and the largest dimension of surface air pores. This data [from samples] allows concrete surfaces to be classified according to their quality levels by [estimating] areas of blemishes in the entire surface of tested specimens.

5.4 Factors affecting size and frequency of bugholes

In the synopsis of an often cited paper, Thomas Reading said: “We need a yardstick for rating concrete surfaces with respect to bugholes, and more know-how on how they can better be controlled.” Then, in the introduction he stated that bugholes are of concern to most owners and architects. He also was struck by the wide differences in the numbers of bugholes from job to job, and even in different parts of the same placement when conditions seemed to be identical. This led him to suggest that it should be possible to better control bugholes if the controlling factors could be established and the knowledge of these factors could then be applied in the field **Reading (1972).**

These observations sum up some of the current problems we face in creating a reliable yardstick, using it as a tool for determining the most crucial controlling factors, then converting that knowledge into processes that concrete producers and contractors could use in the field to restrict the size, number, and concentration of bugholes. Reading didn’t mention, however, one other needed step: The yardstick measurements must be divisible into increments, with differences discernible to the human eye. Do the SVR numbers ranging from 0.3%, 0.6%, 1.0% and 1.2% meet this criteria? Or, is it unlikely that “…appearance, which is essentially an experience of the senses, can ever be expressed in numbers **(Blake et al 1964)**?” That issue will be discussed later in this report.

The crucial controlling factors influencing the formation of bugholes, and the possible interactions between them, can be divided into several categories. These include:

1. Design factors
2. Formwork facing material and condition
3. Form release agent and application thickness
4. Concrete properties
5. Concrete placing and consolidating methods
6. Environmental effects
7. Self-consolidating concrete as a special case

The following is a summary of general beliefs about the effects of each factor and some differing opinions as to the effects found in several studies and papers.

5.4.1 Design factors

Linder (1992) noted that an especially high number of pores can be expected in concretes with a high reinforcement content, particularly with large-diameter closely spaced bars. And also with a low concrete cover over the reinforcement, in particular with aggregate mixtures whose maximum particle sizes exceed the thickness of the concrete cover. **ACI 309.2R-15** advises designers to avoid battered forms and complex design details. As noted in this literature review, battered forms almost always result in excessive numbers of bugholes. Complex details such as a thin sections with congested reinforcement are also a problem, primarily because adequate consolidation is difficult. **ACI 303R-04** deals with this in some detail, as follows:

- In walls and columns, a 5 in. (125 mm) minimum space between vertical mats of reinforcement is recommended to allow concrete placement and consolidation.
- At least a 4 in. (100 mm) space should be provided between one form face and the reinforcement in a wall containing a single mat of reinforcement.
- When practical, the single mat of reinforcement should be located 2 in. (50 mm) from the architectural face so that the concrete may be vibrated between the reinforcement and the back form. If clear space is not adequate, shadowing may occur.
- To facilitate placement of concrete and lessen the possibility of rust stains, the minimum clear distance between bars and the minimum cover for beams as permitted by ACI 318 should be increased to the following values: The horizontal clear distance between bars should be 2 in. (50 mm), 1.25 times the bar diameter, or 1.75 times the maximum aggregate size, whichever is largest; and The horizontal clear distance between bars and the form should be 2 in. (50 mm), 1.25 times the bar size, or 1.5 times the maximum aggregate size, whichever is largest.

Smith (1984) indicated that the structural engineer should consider the potential for steel congestion, especially at column to beam connections. He said while it may be possible to get all of the reinforcement within the formwork, concrete placement may be difficult, if not impossible. And he added that modification by the structural engineer of the reinforcing steel details, or use of modified architectural concrete mixes may be necessary, with careful consideration given as to the effect on the end appearance

.

5.4.2 Formwork facing material and condition

Linder (1992a) stated that smooth, dense, wet, hard, and rigid forming panels resulted in more porous concrete surfaces than textured, porous, hygroscopic and soft facing materials. A laboratory study by **Samuelsson (1970)** confirmed similar findings by **Kinnear (1964)** that impermeable form materials result in more bugholes. Samuelsson, however, stated that thorough consolidation could produce satisfactory surfaces with steel form facings.

Absorbent facings such as boards or plywood panels result in fewer bugholes, with bugholes that are present being less noticeable as a result of less uniform color and a rougher texture. That permeable form facings can essentially eliminate bugholes has been known since 1941 **(Johnson, W.R. 1941).** Later studies confirmed that even with battered (sloped) formwork, permeable form liners produced virtually bughole-free formed surfaces (**Marosszeky et al 1993), (Tsukinaga, Y. et al 1995), (Malone, Phillip 1999), (Coutinho, Joana Sousa 2001).** According to **(Johnston 2014)**, however, "…increased costs and difficulties associated with the use of such materials have prevented their widespread acceptance."

Condition of the facing material is primarily related to its effect on the ease with which entrapped air voids can rise to the surface. **(Linder 1992(a).** Hardened concrete remnants on used form facings are considered unacceptable for two of the three form-facing categories in Table 3.1c of ACI 347.3R-13 and even a thin film of cement residue on the form facing is acceptable for category FC3 only if it doesn't affect the finished [as-built?] concrete surface.

5.4.3 Form release agent and application thickness

Much has been written about the effects of form release agent and application thickness on bughole formation. In the Appendix C Literature Review, enter "release" as the search term to read what has been published. The majority of findings indicate that:

- Barrier-type agents are more likely to result in more and larger bugholes than are the chemically reactive agents. But some reactive agents may be more effective than others in producing better formed surfaces. **ACI 301-16** tells the contractor to: "Cover formwork surfaces with an acceptable material that inhibits bond with concrete. If a formwork release agent is used, apply to formwork surfaces in accordance with manufacturer's recommendations before placing reinforcement." But **ACI 347R-14** suggests: "Manufacturers' recommendations should be followed in the use of coatings, sealers, and release agents" while further adding: "Independent verification of product performance is recommended before use." **Johnston 2014** indicates that both **ACI 347R** and **ACI 347.3R-13**"**…**recommend independent investigation of performance before using a *new* product." We couldn't find the word "new" in either of the ACI documents, but if this recommendation is to be followed, the word "new" needs to be defined. Does "new" mean a product never used by the contractor or never used with the form facing planned? Or is a new product one that has been on the market less than some number of months? Johnston also indicates that the contractor should be concerned with whether or not the release agent is compatible with admixtures in the fresh concrete and as an aid in producing a stain and blemish-free concrete surface.
- Thin applications of release agents are less likely to result in an unacceptable number, size, or concentration of bugholes. This belief is nearly universal, but **ACI 303R-15** states the following: "In general, the thinner the film of release agent applied to the form, the fewer surface air voids and stains on the hardened concrete. The performance of some release agents, however, is not affected by film thickness [no citation is given to substantiate this claim]. Testing before use is recommended." For architectural concrete, then, thin films may not be needed if testing of the release agent—presumably with a mockup—indicates thick films will produce the desired result.

5.4.4 Concrete Properties

Again, much has been written on the effects of concrete properties on bughole size, number, and concentration as indicated in the literature review. But **Klovas (2016)** concluded: “On the basis of a systematic analysis of scholarly literature there is lack of scientific information on modifications in concrete mixtures needed to obtain high quality surfaces.” Some of the following summaries of others’ findings do not apply to effects of these properties on self-consolidating concrete (SCC) so SCC will be dealt with separately.

5.4.4.1 Slump is not a good predictor of the probability of excessive bugholes, although some research **(Samuelsson 1970, Malone 1999)** indicated that higher slumps reduced bughole occurrence. **Thompson (1969)**, with the proviso that sufficient vibration is applied to compact the concrete, suggested that: “…the actual degree of workability itself, as measured by the usual tests, appears to have little influence on the incidence of blowholes.”. **Vikan (2007)** also stated that workable, flowing mixtures, presumably indicating higher slumps, reduced the risk of blowhole formation. **Shilstone (1979)**, however, observed that fluid mixes, while initially appearing to aid in achieving almost void free surfaces, led to a high incidence of voids with a thin cover of cement paste that could later be exposed. pinholes in the finished surface—see also **Ichimaya et al (2005)**. **Berger (1977)** noted a similar situation when concrete surfaces are painted. Most of the pinholes Shilstone describes, he believes are entries to larger voids immediately below the surface that may later be exposed. **Klovas and Dauksys (2013)**, in a study of form release application thickness, found that higher quality concrete surfaces were obtained by using more fluid concrete mixtures (Flow table value 720 mm) as compared with less fluid (525 mm flow) mixtures. Later, however, **Klovas (2016)**, on the basis of his work, stated bluntly that concrete slump alone cannot be linked with the formed concrete surface quality. Because slump depends on so many variables that include water content, admixtures used, and aggregate grading, Klovas’ conclusion is not surprising. Properties such as filling ability (Unconfined flowability ASTM C1611), passing ability (ASTM C1621; also, U-box or L-box test), viscosity or yield stress (V-funnel test), or slump flow or rapid slump flow loss. (ASTM C1611) are likely to be better predictors of surface quality than slump **(Szcesy, Richard, and Mohler, Nathaniel 2015)**. See the section on self-consolidating concrete for more information on SCC and flowing concrete.

5.4.4.2 Air content effects on bugholes are related to whether or not the air voids are entrapped air or entrained air. **Vikan (2007)** states that: “Blowholes result from the migration of entrapped air (and to a lesser extent water) to the fresh concrete-form interface during placement and consolidation. During consolidation, the densification and subsequent volume shrinkage of the fresh concrete forces entrapped air and excess water out of the cement matrix. The water will then tend to migrate upward due to its relatively low density and become bleed water. The air bubbles, however, seek the nearest route to reach pressure equilibrium. For a vertical form, the closest distance for the air bubbles' migration is to the interior form surface." Further, she states that: "A proper amount of vibration sends both entrapped air and excess water to the free surface of the concrete – either vertically winding through the matrix or laterally in a direct route to the form wall. When impermeable forms are used, more vibration is necessary to move the air voids to the free surface of the concrete." **ACI 309.2R-15** recommends avoiding concretes with high entrapped air contents.

The reported effects of entrained air are varied. Some sources advise avoiding the use of air-entrained concrete to reduce bugholes, usually based on the belief that entrained air increases stickiness of the concrete **(Shilstone 1979, Ford 1992, Anon 2005, Cresset 1990).** Another source says high air contents *may* increase incidence of surface voids **(Houston 1967),** while **Samuelsson (1970)** says the prevalence of surface voids could be reduced by using air-entraining agents, probably because they act as lubricants in eliminating the larger accumulations of air. **Klovas (2016)** noted that:, "An increase of the air-entraining admixture dosage resulted in decreased yield stress and plastic viscosity values. It also had a positive influence on the formed concrete surface quality. Based on this information, it is difficult to determine whether or not entrained air is harmful or beneficial in decreasing bughole incidence.

5.4.4.3 Aggregate grading, especially an increase in the fine fractions, does seem to have a positive effect in reducing bughole incidence, although oversanded mixtures may result in more bugholes. **Thompson (1969)** said: **"**It is well known to designers that a change of as little as three percent in the sand content often noticeably improves a mix, and such a change can assist in reducing blowholes under a given set of circumstances." **Linder (1992a)** refers to effects of both cement and aggregate fines on surface voids: "Air voids occur in the core of the concrete structure in about uniform distribution and to a lesser content than in the edge zone, where the cement paste and fine cement mortar contents are much higher, keeping the tiny air bubbles from rising and exiting." **Samuelsson (1970)** asserted that**: "**A *deficit* of fine aggregate passing the No. 60 sieve must be avoided" but **Shilstone (1979)** stated that *excessive* minus-50 mesh sand resulted in mixture stickiness, with stickiness being one of the factors named as contributing to bugholes **(Vikan 2007)**. To reduce bugholes, **Stamenkovic (1973)** suggests using fine sand with a high surface area. He says increasing sand content is not as effective as using finer sand (particles passing the No. 50, 100, and 200 sieves). He also recommends using smaller coarse aggregates, with particles more nearly spherical, and avoiding crushed aggregate.

These observations indicate that sand content is not as important as the amount of fines passing the No. 50 sieve in controlling bughole incidence. Excessive amounts of such fines, however, may increase bugholes. The suggestion regarding smaller coarse aggregate can be related to design considerations such as reinforcing bar spacing and allowable clear cover.

5.4.4.4 Cement content

According to **Thompson (1969)** rich (higher cement content) mixtures tend to exhibit fewer blowholes than leaner mixtures of the same workability. But he adds that the effect of the cement content on a mix made with a well-graded aggregate appears to be negligible. **Ford (1992)**, however, advises avoiding high paste contents to reduce the occurrence of bugholes. **Klovas (2016)** concluded that: "Increasing fine particles (cement together with sand not exceeding 0.25 mm size) from 441 to 600 kg/m^3 significantly reduced the mixture's yield stress and its plastic viscosity. It also significantly reduced the ratio between the areas of surface blemishes and the total specimen size [SVR] from 17.3 to 0 %.

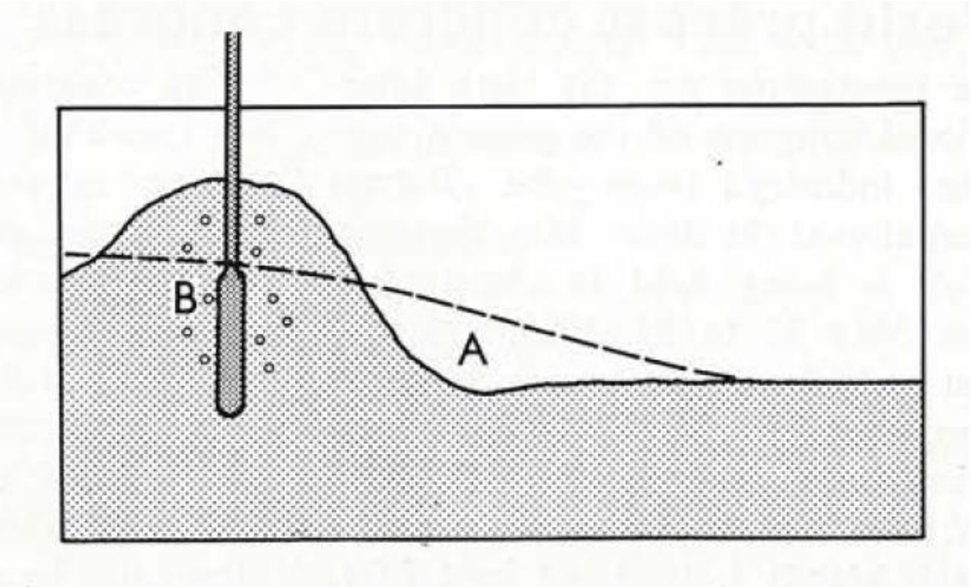
5.4.4.5 Ratio of water to cementitious materials

Linder (1992) postulated that an especially high number of pores can be expected in concretes with high water-cement ratios because rapid liquefaction encloses the pores. **Houston (1967)** concluded that high water contents *may* increase incidence of surface voids, with a target water-cement ratio of 0.49, but results were not [statistically] conclusive.

5.4.5 Placing and consolidating methods

Vikan (2007) indicates that improper vibration is perhaps the most influential cause of bugholes. **Shilstone (1979),** in a table listing contributors to surface finish blemishes of formed concrete, indicated that both excessive free fall and reinforcing – bar interference with the falling concrete could cause blemishes.

Thompson (1969) was the first to note that lateral flow of concrete helped to reduce the number of bugholes. As shown in the figure, he explained that in flowing from the heap at B, lateral flowing concrete at A will have expelled much of the entrapped air and will be relatively free of surface holes when stripped. But at B, where there was less lateral flow, air rising in the vicinity of the vibrator would tend to accumulate and be trapped, with blowholes more severe at that point. The same phenomenon occurs in self-consolidating concrete as seen later.



ACI 303R-04 (2004), however, warned: “The surface of each layer should be sufficiently level so that the vibrator does not move the concrete laterally, as this might cause segregation.” **ACI 309.2R-15** recommends limiting the depth of placement layers to reduce bughole formation, with **ACI 303R-04** suggesting that, with proper proportioning, depending on the width of the forms and the amount of reinforcement, lifts can be up to 36 in. (900 mm) deep. ACI 309R-04 adds that deeper lifts, accompanied by additional careful vibration, can be used with high-density forming to eliminate excess surface air voids. **Anon (2008)** suggests placing concrete with maximum vertical rise of 2 m/hr. **ACI 303R-04** indicates that acceleration of the vertical rate of casting, particularly in hot weather, will eliminate or make manageable the problems associated with surface air voids, form spatter, cold joints, and lift lines. **ACI 309.2R-15 (15)**, however indicates that when concrete is stiff, the placing rate must be reduced to allow adequate vibration and reduce bugholes.

With respect to consolidation, Thompson (1969) emphasized the importance of vibration in reducing bughole formation prior to the widespread use of water-reducing admixtures to reduce mixture viscosity. He said: “Several factors influence the formation of blowholes, but by far the most outstanding appears to be the way in which the concrete is placed and compacted.” Samuelsson (1970) agreed, based on his experimental results, stating vibration procedure had the greatest effect on surface appearance and that vibration should be thorough and sufficient. He added that more consolidation is needed with impermeable form facings. Anon (1979) believed using thorough internal vibration followed by low frequency external form vibration was needed to minimize bugholes. Stamenkovic (1973) also suggested controlling bugholes in concrete surfaces by using both internal and external vibration combined with hammering and revibration. Shilstone (1979) believed consolidation is better when the vibrator is rapidly plunged into the lift below, penetrating for the full length of the head, and then extracted slowly with up-and-down surging movements. Slow insertion of the vibrator head, he said, results in entrapment of air below and the surging action during manipulation creates swell forces against the forms, forcing out air bubbles. The Australians (Anon 2008) advise withdrawing the vibrator slowly to allow time for entrapped air to rise, but does not include the recommendation of up-and-down surging movements. They add the general statements to:

  - Consolidate with vibrator of proper size and spacing of insertion points, and use proper technique.
  - Make sure concrete near form is properly compacted.
  - Revibrate the top placement layer at about the same time as if a further layer was being placed on top.

ACI 309R-15 (2015) suggests avoiding use of high-amplitude vibrators or incomplete insertion of the vibrator head, either of which could result in an increased quantity of bugholes. That document also lists the following steps for minimizing bugholes when consolidating concrete:

- Space vibrator insertions at 1.5 times the radius of influence and remove vibrator slowly.
- Consolidate each concrete layer from the bottom up.
- Increase vibration duration when using impermeable forms.
- Be sure vibrator penetrates the previous layer.
- When practical, use a 2-1/2-in. diameter vibrator of high frequency and medium to low amplitude. Note that **Shilstone (1979)** believed low amplitude vibrators contributed to surface blemishes.
- Revibrate at the latest possible time at which the vibrator head will penetrate the concrete under its own weight. This is helpful with higher-slump mixtures, especially in the upper portion of the placement.

5.4.6 Environmental effects

Thompson (1969) noted that temperature of the form facing could have a marked effect on the surface finish. Placing high or medium workability concrete against cold surfaces could result in sand-streaking because of delayed setting and an increased duration of bleeding. He said, however, that temperature of the mass of concrete or the form face appeared to have a negligible effect on the incidence of blowholes.

5.4.7 Self-consolidating or flowing concrete as a special case

Use of self-consolidating concrete (SCC), although mentioned only once in ACI 347.3R-13, is one of the best strategies for concrete contractors' and producers to reduce bugholes in formed surfaces. Using flowing concrete to aid in consolidation is another option. Unlike SCC, flowing concrete does require vibration when used **(Anon 2008).** The major disadvantage of either option for contractors is increased concrete cost related to admixture usage and quality. But if the surface void ratio is to be held to 0.3% or 0.6%, use of SCC or flowing concrete offers more chance of success than other options.

ACI 227R-07 states that: "The typically lower *w/cm* of SCC, combined with the better homogeneity characteristics when compared with conventional concrete, can improve the interface zone of cement paste and aggregate, improve surface quality that results in fewer bugholes and air voids…" and: "One benefit of SCC is that it provides improved surface appearances and aesthetics in finished concrete. Pour lines, bugholes, honeycombs, and other surface imperfections are largely reduced."

In several ways, proportioning, placement, and consolidation methods differ from those for non-self-consolidating concrete. **Anon (2009)** lists multiple factors that affect the final surface quality of the concrete element. These include:

- The mix composition of the product.
- The quality of the formwork surfaces.
- The quality of the formwork release agent and its interaction with the SCC mixture.
- The placing methods and procedures utilized.

These factors are covered extensively in the literature. In Appendix C, see **Gram (2004), Ramsburg (2004), Ichimaya et al (2005), RILEM (2006), Vikan (2007),Silva et al (2011), Silva and Stemberk (2013), Szcesy and Mohler (2016)** and **Moruza and Ozildirim (2017).** These publications, however, make it clear that merely using SCC does not guarantee a surface free of most bugholes. The literature consistently states that, because of the many controllable and some not easily controllable variables, quality assurance is of even greater importance when SCC or flowing concrete is used than when conventional (vibrated) concrete is used. For instance, **Moruza and Ozildirim (2017)** indicated that reducing bugholes in precast bridge beams required higher slump flow values. However, this created a tradeoff that presented the risk of lower mixture stability. They stated that care was exercised to use a target value with some tolerance, but to avoid slump flow values close to the high or the low limits of the specified tolerance. Proper use of fine materials and viscosity-reducing admixtures helped to keep the SCC stable.

CHAPTER 6 TESTING PROGRAM

As discussed in Chapter 1, researchers anticipated three potential problems when surface void ratio (SVR) is "…required to be determined if the entire impression of the surface does not meet the contract expectation." (page 6 in ACI 347.3R-13). The problems centered on three concerns:

- The SVR determination is made on one sample from the building unit under consideration, but with no details given as to how the sample is chosen.
- Repeatability and reproducibility of the suggested method for measuring SVR. This requires superimposing a rectangle over each void such that about as much void area falls outside the rectangle as non-void area falls inside, measuring the area of each rectangle, summing the areas and expressing that sum as a percentage of the sample area. This method is not included in the 2008 or 2015 versions of the German document, and ACI 347.3R-13 provides no data regarding variability of results using the method.
- There is no rationale or data provided for the choice of the four not-to-exceed SVR values given in Table 3.1d of ACI 347.3R-13.

Testing was needed to further explore these issues.

6.1 Initial classroom testing

In the first testing phase of this research, co-investigator Dr. Heather Brown and her Concrete Industry Management (CIM) students at Middle Tennessee State University experimented with several alternative methods for measuring irregularly-shaped void areas. They considered:

- Time needed for measurement
- Cost, if any, of equipment needed
- Repeatability of results using different methods

Initial measurements were made on photographs of formed concrete surfaces containing bugholes of varying size and frequency. These photos were taken from the ASCC *Guide to Surface Finish of Formed Concrete* and are labeled P2, P4, and P5 in **Figs. 6.1 through 6.3**. The photo size was not 2-ft x 2-ft, but the objective of this exercise was to determine repeatability and reproducibility, plus ease and cost of measuring SVR. Measuring methods included **(Fig. 6.4)**:

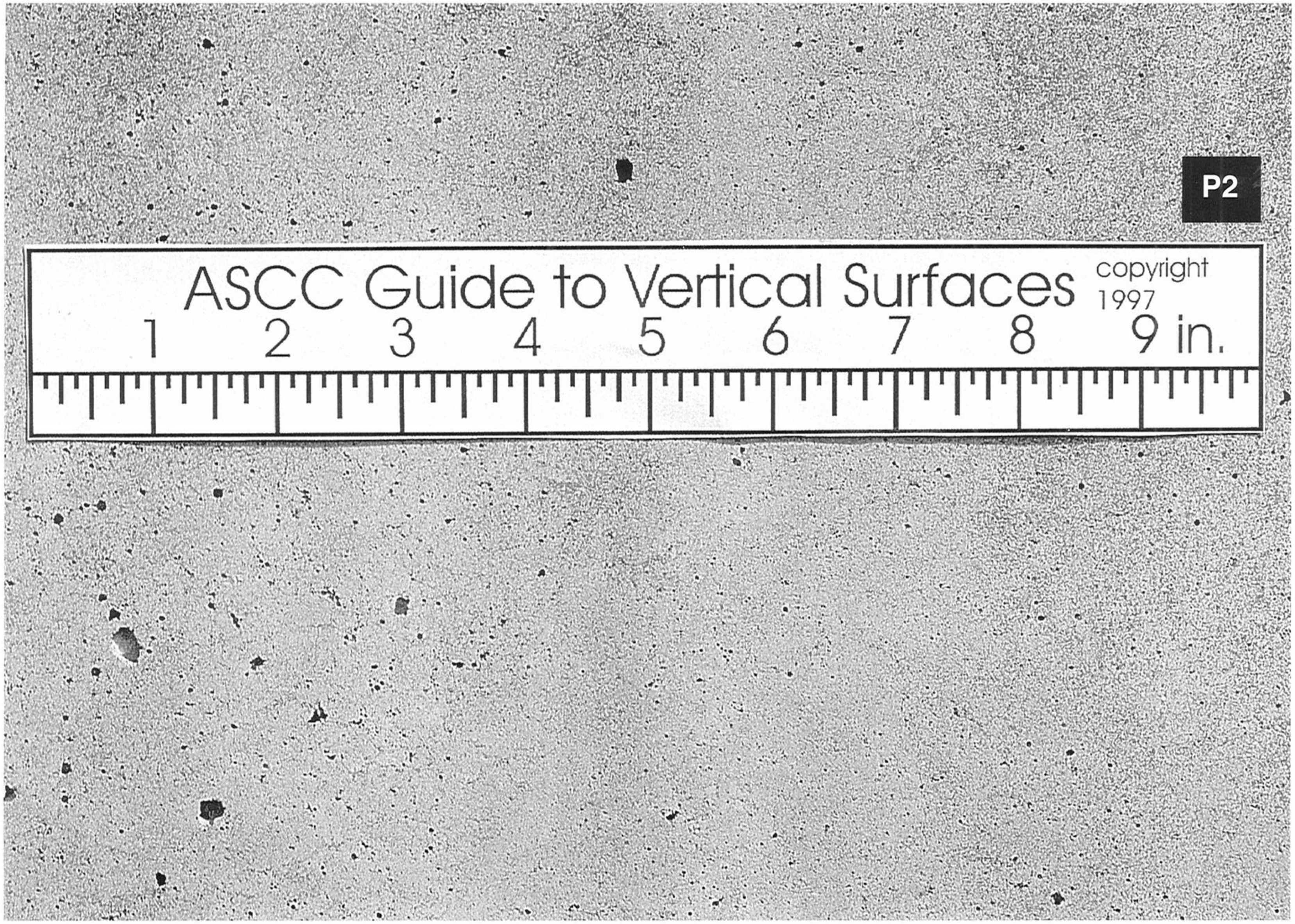


Fig. 6.1 ASCC Photo 2 of off-the-form concrete finish with small bugholes area

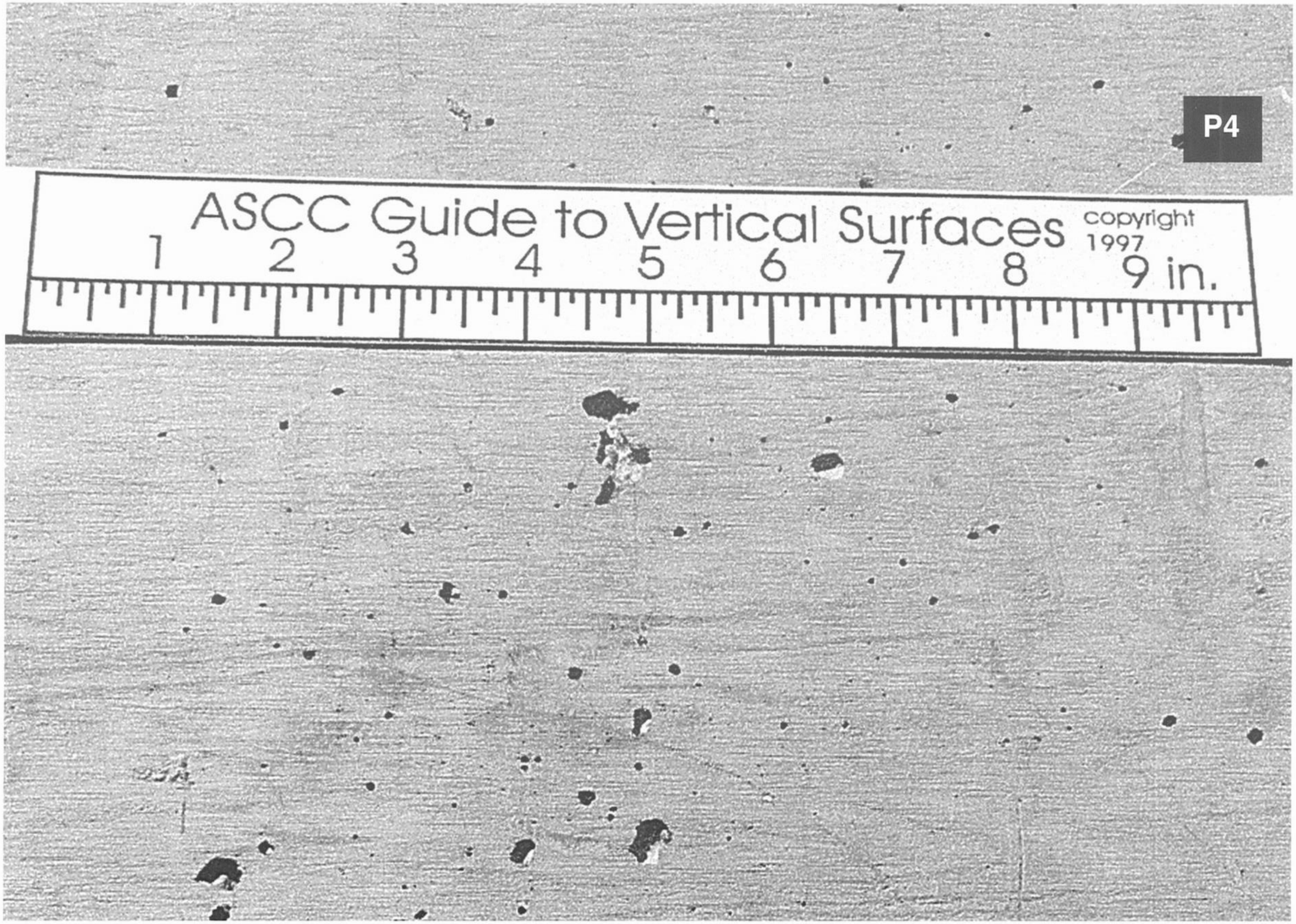


Fig. 6.2 ASCC Photo 4 of off-the-form concrete finish with medium bughole area

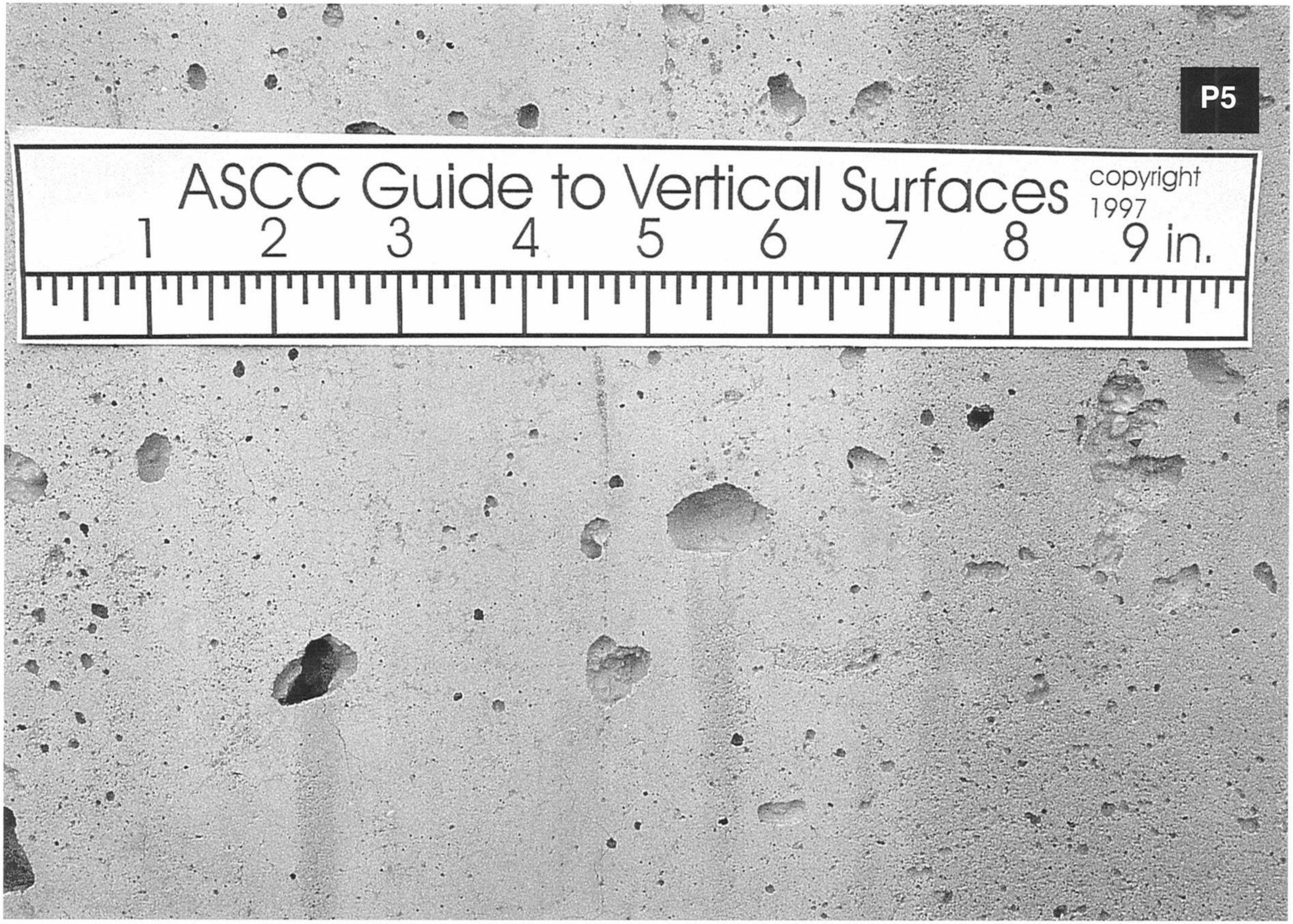
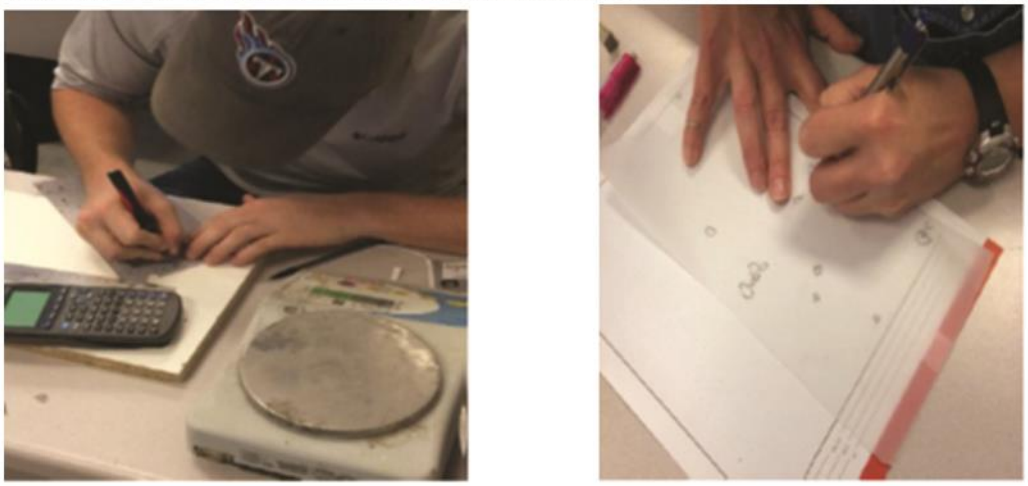


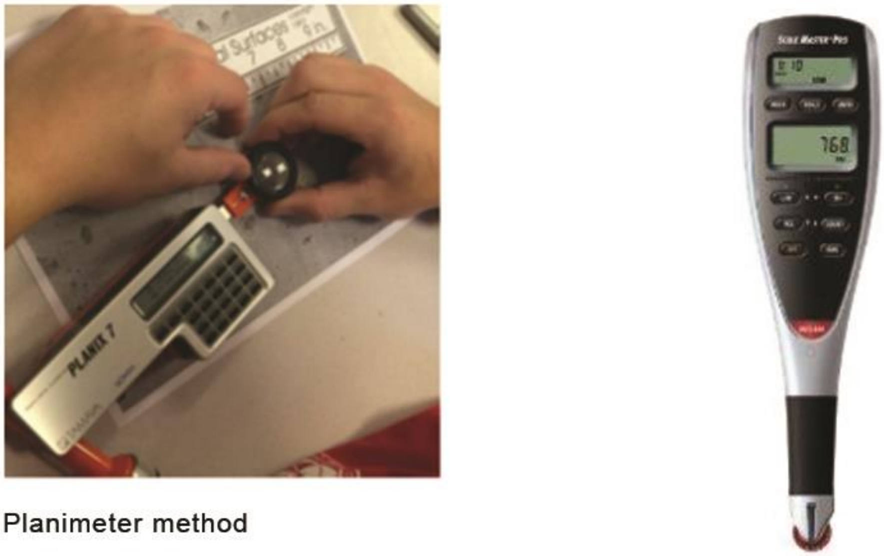
Fig. 6.3 ASCC Photo of off-the-form concrete finish with larger bughole area*

Fig. 6.4 Void area measurement methods first used to determine SVR from photos



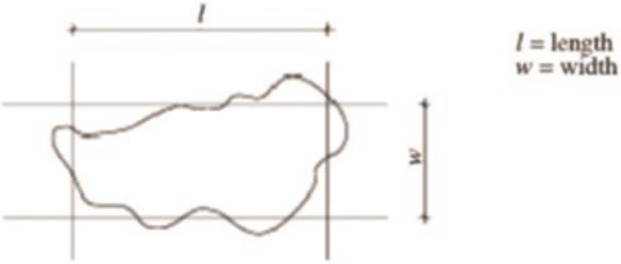
Weighing paper cut-outs method

Counting squares method



Planimeter method

Digital measurement of bughole perimeter



Rectangle method

Using the superimposed rectangle method described in ACI 347.3R.

- Tracing the voids on graph paper, then counting squares of known area and estimating partial squares.
- Weighing a heavy paper sheet, tracing voids onto the sheet, cutting out the voids and then weighing them.
- Using a digital device to measure the perimeter of each void, assuming the perimeter is the circumference of an equivalent circle, and calculating an equivalent diameter and area.
- Using a planimeter to measure the area of each void.

Results of the first sets of measurements are shown in **Table 6.1**. Based on this initial experience with the various methods, the weighted paper method was judged to require too much time to accurately cut out the void images. The digital device method resulted in difficulties tracing the smaller voids. The rectangle, graph paper, and planimeter, methods were chosen for further use.

Table 6.1 Initial Measurements SVR on photos

	Photo P4		Photo P5	
Method	**Average, %**	**St. Dev.,%**	**Average, %**	**St. Dev., %**
• Rectangle	1.7	-----	6.4	0.1
• Count squares	0.9	0.2	5.2	0.6
• Weighted paper	2.6	0.1	6.2	1.1
• Digital perimeter	1.5	-----	5.0	-----
• Planimeter	2.5	0.4	6.5	0.5

6.2 Construction and field testing of a wall

To transfer the four measurement methods from a laboratory to a field environment, CIM students first set forms for a U-shaped test wall on the MTSU campus, placed concrete, and stripped the forms a day later. Appearance of the wall immediately after form stripping and six weeks later is shown in **Fig. 6.5**. Details for the concrete mixture, forms, release agent, and placing methods, plus photos are given in Appendix D.

Fig. 6.5 MTSU test wall immediately after form stripping and six weeks later

Dr. Brown and lab manager, Jason Crabtree, supervised several teams of students initially employing the four methods described previously to measure void areas multiple times in four 2-ft by 2-ft samples on the wall **(Fig. 6.6)**. Voids were measured directly on the wall using the rectangle method and were then traced on Mylar sheets. The sheets were moved to on-site tables where voids were measured by the other two methods. Results are shown in **Table 6.2**. Data from these measurements were used for initial estimates of the SVR standard deviation for each of the four methods. When these data were presented to ACI Committee 347, committee member Dr. David Johnston suggested using a circle template superimposed over the bughole in the same manner as the rectangle and as described in the 8th edition of ACI SP-04 (14), *Formwork for Concrete.* This method was adopted for some measurements that followed.

Table 6.2 Initial SVR Measurements on MTSU Test Wall

Area 1	Voids (Sq. In.)	Average Sq. In.	% Voids	SD
Rectangle	3.81	2.79	0.48%	1.02
	1.77			
Counting Squares	3.59	3.21	0.56%	0.38
	2.83			
Planix 7	3.93	6.82	1.18%	2.89
	9.70			
Average sq. in.	**4.27**	**Average % Voids**	**0.74%**	

Area 2	Voids (Sq. In.)	Average	% Voids	SD
Rectangle	4.55	3.48	0.60%	1.08
	2.40			
Counting Squares	1.87	1.91	0.33%	0.03
	1.94			
Planix 7	6.00	4.50	0.78%	1.50
	3.00			
Average sq. in.	**3.29**	**Average % Voids**	**0.57%**	

Area 3	Voids (Sq. In.)	Average	% Voids	SD
Rectangle	3.91	3.34	0.58%	0.57
	2.77			
Counting Squares	4.12	3.51	0.61%	0.62
	2.89			
Planix 7	11.08	8.97	1.56%	2.12
	6.85			
Average sq. in.	**5.27**	**Average % Voids**	**0.91%**	

Area 4	Voids (Sq. In.)	Average	% Voids	SD
Rectangle	2.91	2.17	0.38%	0.75
	1.42			
Counting Squares	1.35	1.30	0.23%	0.05
	1.25			
Planix 7	3.63	3.60	0.63%	0.03
	3.57			
Average sq. in.	**2.36**	**Average % Voids**	**0.41%**	

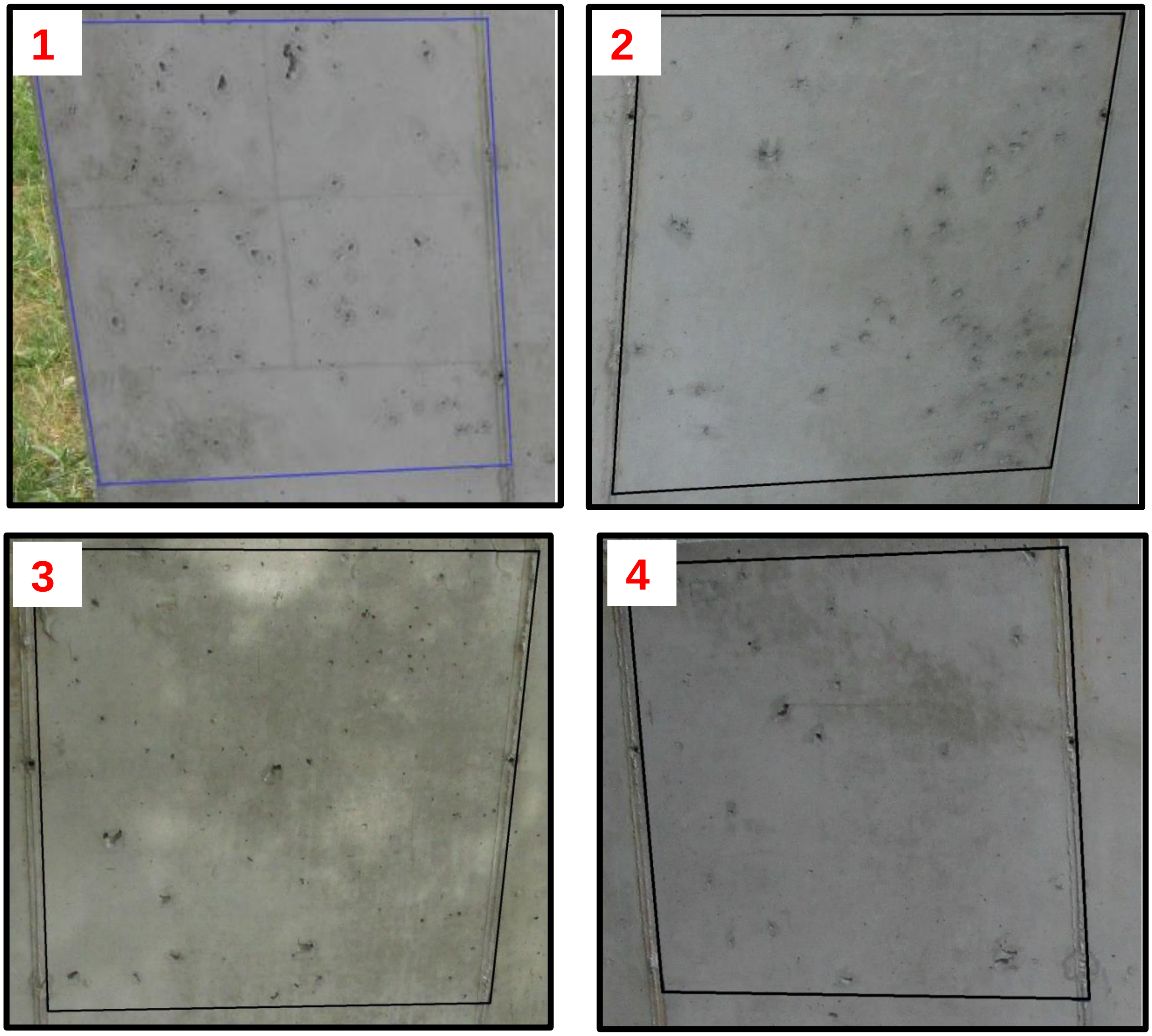
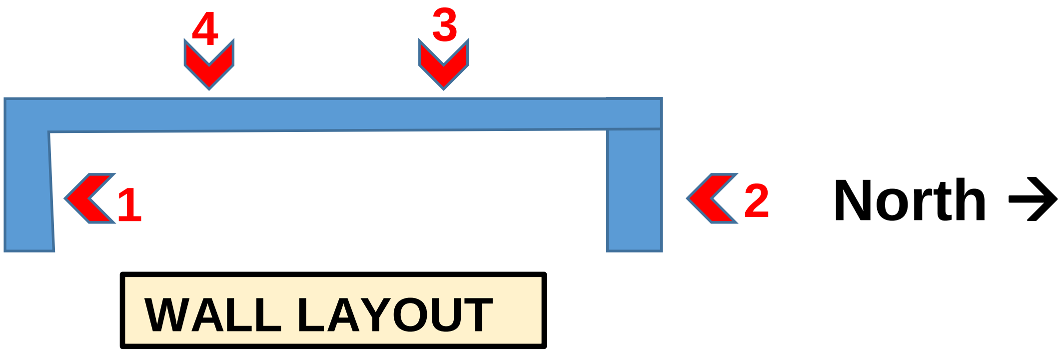


Fig. 6.6 Location of first four samples measured for SVR on MTSU test wall.



Five more sample locations were randomly chosen, marked, and measured by two groups of students. These later measurements, plus the initial four, were used in estimating how many samples were needed to reduce sampling error. Results using the counting squares method on the wall are shown in **Fig. 6.7**. Convergence of the running averages for SVR measured by two groups was used to estimate the number of samples needed for the wall.

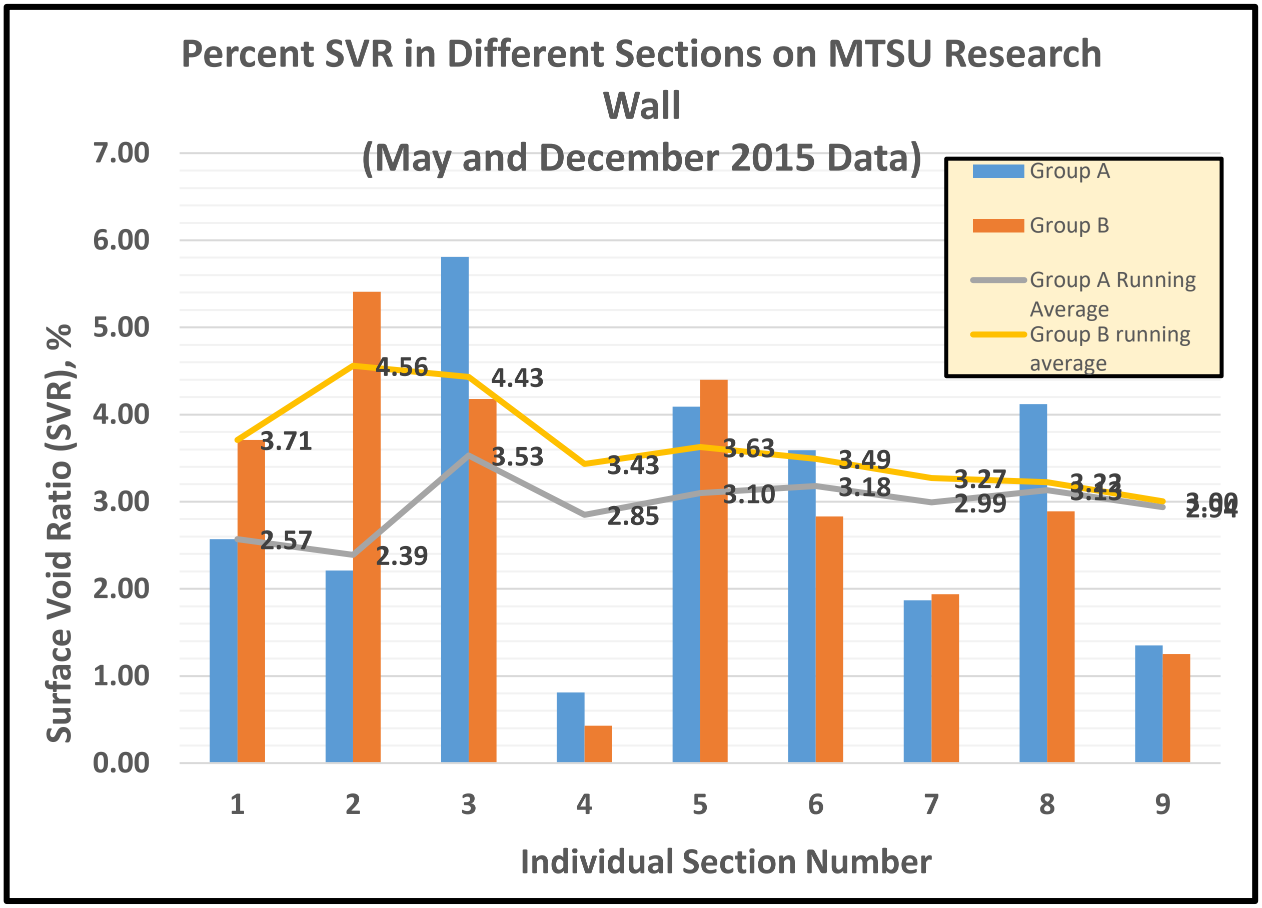


Fig. 6.7 Variation in SVR as affected by sampling and operator (Counting squares method)

Based on convergence of the SVR running averages, it appeared that six to nine samples were needed for a wall with an average SVR of about 3%. **Fig. 6.8** presents the count-squares data from all nine sample locations and the chart indicates that there were wide variations in SVR for sample-to-sample testing and within-sample testing (Group A vs. Group B). All of the data from the MTSU wall measurements were the basis for sampling and measurement protocols used by teams from all of the four CIM universities in measuring as-built walls.

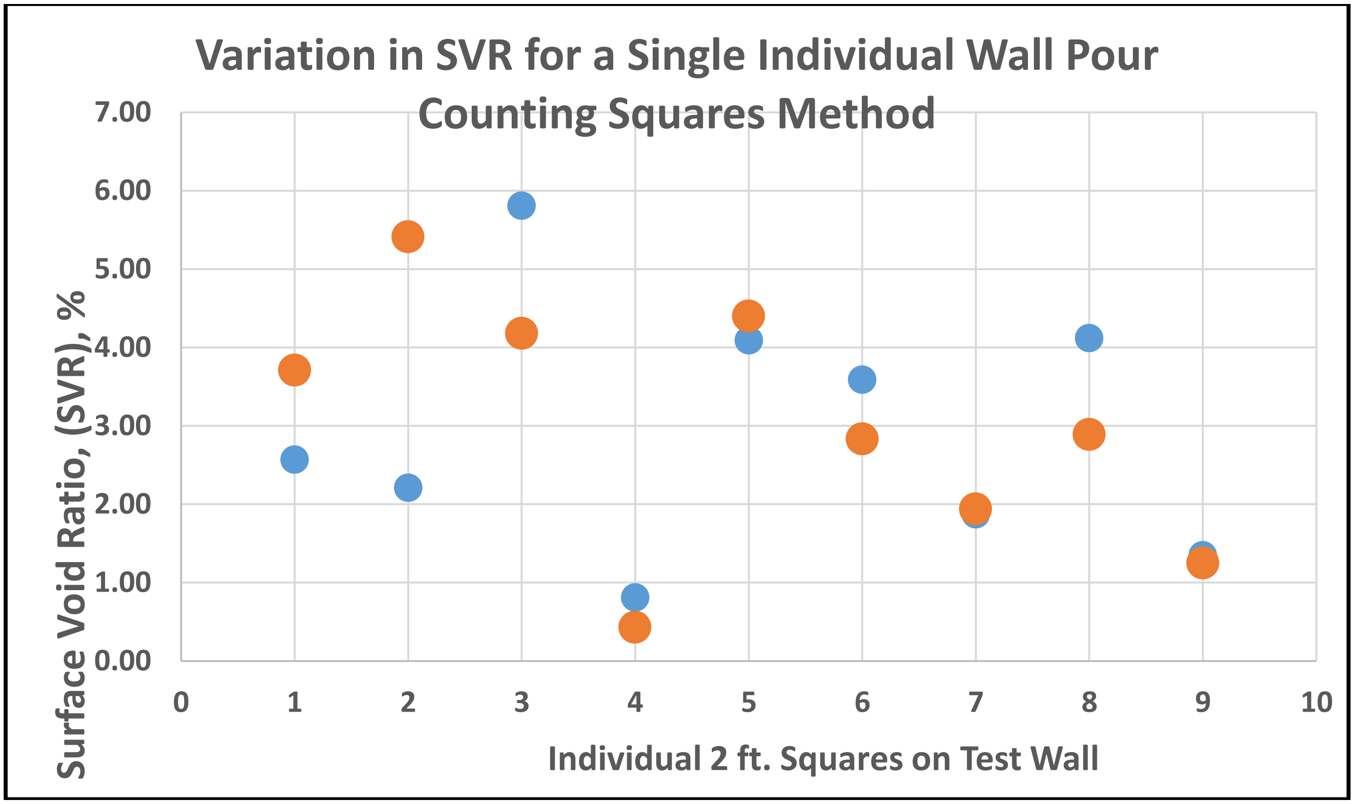


Fig. 6.8 SVR of MTSU research wall as affected by sample location and operator

6.3 Further measurements of SVR using ASCC photos

During the World of Concrete 2016 exposition, Drs. Brown, Malisch, and Suprenant met with faculty members from the three other universities that offer the CIM program: California State University—Chico, New Jersey Institute of Technology, and Texas State University. The purpose was to familiarize them with the ACI 347.3R-13 criteria for SVR1 through SVR4 classifications, and measurement methods to be used. To give the CIM student researchers experience in measuring SVR, the same three ASCC photos were provided for use in making measurements in the classroom prior to making measurements on as-built walls in their geographic area. Three methods were used:

- Rectangle procedure recommended in ACI 347.3R-13,
- Circle template procedure recommended in ACI SP 4, and
- Counting squares procedure using 10 sq/in. tracing paper.

Due to limited availability of student researchers, fewer data points were developed by CIM universities other than MTSU. A summary of measurements taken for each of the three methods, including the data from MTSU is shown in **Tables 6.3, 6.4, and 6.5**. As noted, In Table 6.3, Grubbs' test for outliers eliminated one data point for each of the three methods resulting in the mean and standard deviation being recalculated based on 12 instead of 13 data points.

Table 6.3 SVR Measurements on ASCC Photo 2 by Four CIM Universities

Method Used Photo 2	Rectangle	Count squares	Circle Template	University
Operator 1	0.2%	0.7%*	0.6%*	MTSU
Operator 2	0.3%	0.4%	0.4%	MTSU
Operator 3	0.2%	0.3%	0.2%	MTSU
Operator 4	0.46%*	0.3%	0.1%	MTSU
Operator 5	0.3%	0.3%	0.4%	MTSU
Operator 1	0.3%	0.2%	0.2%	NJIT
Operator 2	0.2%	0.3%	0.3%	NJIT
Operator 3	0.2%	0.2%	0.2%	NJIT
Operator 1	0.3%	0.2%	0.2%	Chico
Operator 2	0.3%	0.2%	0.3%	Chico
Operator 3	0.3%	0.3%	0.2%	Chico
Operator 1	0.3%	0.3%	0.2%	Texas St.
Operator 2	0.3%	0.3%	0.2%	Texas St.
No. of points	12	12	12	
Mean	0.3%	0.3%	0.2%	
Std. dev.	0.05%	0.05%	0.09%	
Coef. of variation	17%	17%	45%	

* Outlier not included in calculating mean and standard deviation

Table 6.4 SVR Measurements on ASCC Photo 4 by Four CIM Universities

Method Used Photo 4	Rectangle	Count squares	Circle Template	University
Operator 1	1.7%	1.0%	2.2%	MTSU
Operator 2	1.4%	0.7%	0.9%	MTSU
Operator 3	1.2%	1.1%	1.4%	MTSU
Operator 4	1.8%	1.2%	1.2%	MTSU
Operator 5	1.2%	0.1%	0.9%	MTSU
Operator 1	1.0%	0.5%	0.6%	NJIT
Operator 2	0.7%	0.4%	1. 2%	NJIT
Operator 3	0.5%	0.6%	0.5%	NJIT
Operator 1	1.3%	1.4%	1.2%	Chico
Operator 2	1.8%	1.7%	1.6%	Chico
Operator 3	1.0%	0.9%	1.0%	Chico
Operator 1	1.4%	1.1%	1.1%	Texas St.
Operator 2	1.6%	1.3%	1.2%	Texas St.
No. of points	13	13	13	
Mean	1.3	0.9	1.2	
Std. dev.	0.4	0.4	0.4	
Coef. of variation	31%	44%	33%	

Table 6.5 SVR Measurements on ASCC Photo 5 by Four CIM Universities

Method Used **Photo 5**	**Rectangle**	**Count squares**	**Circle Template**	**University**
Operator 1	6.4%	4.8%	7.8%	MTSU
Operator 2	6.5%	5.6%	3.7%	MTSU
Operator 3	6.2%	5.4%	4.0%	MTSU
Operator 4	6.1%	6.0%	4.9%	MTSU
Operator 5	6.2%	5.7%	6.6%	MTSU
Operator 1	5.0%	2.1%	3.4%	NJIT
Operator 2	3.2%	1.9%	3.2%	NJIT
Operator 3	2.7%	2.2%	3.0%	NJIT
Operator 1	7.0%	5.4%	5.2%	Chico
Operator 2	4.8%	5.5%	5.8%	Chico
Operator 3	5.6%	5.1%	5.4%	Chico
Operator 1	6.0%	5.1%	5.0%	Texas St.
Operator 2	5.7%	5.2%	5.2%	Texas St.
No. of points	13	13	13	
Mean	5.5%	4.6%	4.6%	
Std. dev.	1.3%	1.5%	1.1%	
Coef. of variation	24%	33%	24%	

Student researchers from the other three CIM universities also recorded the time needed to measure voids on the three photos using the three methods. Results are shown in **Tables 6.6, 6.7** and **6.8.** As expected, the average time for measurement increased as the SVR increased. The rectangle method was the most time-consuming method and the circle template method took slightly less time than the counting squares method. In Table 6.7, for instance, measuring SVR on ASCC Photo 4 (SVR range of 0.9% to 1.3%) required an average time from 17 min. for the counting squares method to 26 min. for the rectangle method. The rectangle method was also the most time-consuming of other methods used in this study. Although the counting-squares and circle-template methods consumed less time, the variability from those methods could still result in the SVR for a given photo into two or more of the four categories in ACI 347.3R-13. Thus, more repeatable and reproducible measurement methods would be needed to make the SVR appropriate for assessing the size and number of bugholes.

Table 6.6 Time Needed for Measuring SVR for ASCC Photo 2
SVR range = 0.2% to 0.3%

Method Used **Photo 2**	**Rectangle**	**Count squares**	**Circle Template**	**University**
Operator 1	20 min.	10 min.	13 min.	NJIT
Operator 2	20 min.	10 min.	10 min.	NJIT
Operator 3	21 min.	15 min.	15 min.	NJIT
Operator 1	10 min.	5 min.	5 min.	Chico
Operator 2	7 min.	3 min.	3 min.	Chico
Operator 3	7 min.	3 min.	4 min.	Chico
Operator 1	30 min.	15 min.	10 min.	Texas St.
Operator 2	12 min.	11 min.	11 min.	Texas St.
Mean time	16 min.	9 min.	9 min.	
Std. dev.	8 min.	5 min.	4 min.	
Coef. of Var.	50%	56%	44%	

Table 6.7 Time Needed for Measuring SVR for ASCC Photo 4
SVR range = 0.9% to 1.3%

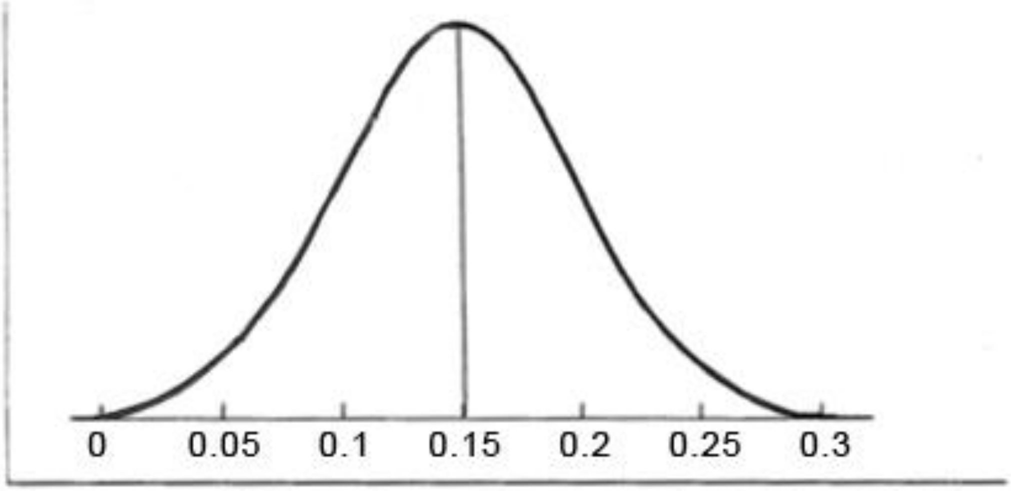
Method Used **Photo 4**	**Rectangle**	**Count squares**	**Circle Template**	**University**
Operator 1	35 min.	20 min.	30 min.	NJIT
Operator 2	35 min.	20 min.	25 min.	NJIT
Operator 3	31 min.	22 min.	33 min.	NJIT
Operator 1	25 min.	15 min.	10 min.	Chico
Operator 2	21 min.	10 min.	6 min.	Chico
Operator 3	16 min.	8 min.	7 min.	Chico
Operator 1	20 min.	10 min.	15 min.	Texas St.
Operator 2	28 min.	30 min.	25 min.	Texas St.
Mean	26 min.	17 min.	19 min.	
Std. dev.	7 min.	8 min.	11 min.	
Coef. of Var.	27%	47%	58%	

Table 6.8 Time Needed for Measuring SVR for ASCC Photo 5
SVR range = 4.6% to 5.5%

Method Used **Photo 5**	**Rectangle**	**Count squares**	**Circle Template**	**University**
Operator 1	45 min.	45 min.	39 min.	NJIT
Operator 2	45 min.	45 min.	30 min.	NJIT
Operator 3	41 min.	43 min.	34 min.	NJIT
Operator 1	60 min.	15 min.	15 min.	Chico
Operator 2	35 min.	20 min.	20 min.	Chico
Operator 3	49 min.	22 min.	20 min.	Chico
Operator 1	40 min.	30 min.	20 min.	Texas St.
Operator 2	41 min.	42 min.	47 min.	Texas St.
Mean	45 min.	33 min.	28 min.	
Std. dev.	8 min.	12 min.	11 min.	
Coef. of Var.	18%	36%	39%	

6.4 Preliminary assessment of measurement precision based on SVR classifications

In the German document on which ACI 347.3R-13 is based, each of the four SVR categories is separated by an SVR interval of 0.3%. Assuming the SVR values for a sample are normally distributed, with a range of ± 3 standard deviation units about the mean, the standard deviation would be 0.3%/6 = 0.05% and this range would encompass 99.7% of the data, as shown below.



Assuming a normal distribution, the mean SVR ± three standard deviation units includes 99.7% all of the data. For a CSC4 category (maximum SVR = 0.3%) the standard deviation would be 0.05%.

This standard deviation is an indicator of the variability due to measurement, and is roughly analogous to the within-batch variation described in *Guide to Evaluation Strength Test Results* (ACI 214R-11) as due to testing. Note in Table 6.3 that for Photo 2, the mean SVR was about 0.3%--the upper SVR4 limit in both the German document and ACI 347.3R-13 for a CSC4 category. The standard deviations for both the rectangle and counting squares methods were 0.05%. This indicated that due to measurement error alone, the entire SVR limit is taken up by measurement error. That permits no allowance for variations in SVR due to variations in the concrete contractors' materials or methods.

An analysis of SVR measurements of off-the-form surfaces from 2x2-ft sample on as-built walls was undertaken next. The wall measurements were also used to estimate variability from sample to sample, which is similar to the batch-to-batch variations described in ACI 214R-11.

6.5 SVR measurements of as-built walls

During the World of Concrete 2016 exposition, leaders of the four CIM universities had also been provided with sampling and measurement protocols, instructions for choosing random samples, and data sheets for use in their work in determining the SVR of as-built walls. (Appendix D). The three methods used for SVR measurements on ASCC photos were also to be used on the 2x2-ft samples chosen for the off-the-form surfaces of walls.

Throughout the next year, teams of student researchers from three of the CIM universities went to the field to measure SVR for vertical surfaces on active construction sites or on existing buildings. Due to availability of a varying number of student researchers the number of samples taken varied, as did the number of structures on which SVR was measured.

Student researchers at MTSU measured SVR on two cast-in-place residential foundation walls (**Fig. 6.9**) and a wall in a parking garage and office complex in the Nashville, TN, area (**Fig. 6.10**). A large residential wall cast in plywood forms was reported to have been placed with a 6-in.-slump concrete and consolidated by hitting the form with a rubber mallet. The other, smaller residential wall was placed by pumping into aluminum forms, with no consolidation, and again with a reported 6-in. slump. The contractor for the parking garage wall reported that a 6-in.-slump concrete was used and placed with no vibration. Results of all the SVR measurements are shown in **Table 6.9 and Figs. 6.11 through 6.13.**

Large residence wall

Small residence inside wall

Small residence on outside wall

Fig. 6.9 Residential walls measured for SVR by MTSU student researchers

Fig. 6.10 Parking garage and office complex walls measured for SVR by MTSU student researchers

Table 6.9 MTSU Field Measurements of SVR on As-Built Walls

Description	**Total Area, square inches**			**SVR, %**		
	Circles	Squares	Rectangles	Circles	Squares	Rectangles
Job 1, Large Residential Basement						
Operator 1	1.22	1.17	0.97	0.21	0.20	0.17
Operator 1	2.4	2.51	1.95	0.42	0.44	0.34
Operator 2	2.9	3.36	6.45	0.50	0.58	1.12
Operator 2	0.49	0.78	2.15	0.09	0.14	0.37
Operator 3	3.46	2.89	5.72	0.60	0.50	0.99
Operator 3	1.75	1.61	2.58	0.30	0.28	0.45
Operator 4	0.6	1.07	1.43	0.10	0.19	0.25
Operator 4	3.02	2.4	3.1	0.52	0.42	0.54
Mean, %				0.3	0.3	0.5
Std. deviation, %				0.2	0.2	0.4
Coef. of Variation, %				59	47	69
Job 2, Small Residential Basement						
Operator 1	1.77	1.7	1.63	0.31	0.30	0.28
Operator 1	0.21	0.21	0.13	0.04	0.04	0.02
Operator 2	0.65	1.05	1.92	0.11	0.18	0.33
Operator 2						
Operator 3	0.19	0.37	0.35	0.03	0.06	0.06
Operator 3	1	1.25	2.18	0.17	0.22	0.38
Operator 4	0.62	1.35	1.79	0.11	0.23	0.31
Operator 4	1.72	0.97	1.17	0.30	0.17	0.20
Mean, %				0.2	0.2	0.2
Std. deviation,%				0.1	0.1	0.1
Coef. of Variation				67	53	43
Job 3, Parking Garage and Office Complex						
Operator 1	2.4	2.32	2.38	0.42	0.40	0.41
Operator 1	1.24	1.28	1.24	0.22	0.22	0.22
Operator 2	0.65	1.22	2.19	0.11	0.21	0.38
Operator 2	0.83	1.38	2.3	0.14	0.24	0.40
Operator 3	2.04	1.84	3.24	0.35	0.32	0.56
Operator 3	0.37	0.36	0.42	0.06	0.06	0.07
Operator 4	2.12	1.67	2.42	0.37	0.29	0.42
Operator 4	1.6	1.6	2.16	0.28	0.28	0.38
Mean, %				0.2	0.3	0.4
Std. deviation,%				0.1	0.1	0.2
Coef. Of variation,%				54	40	42

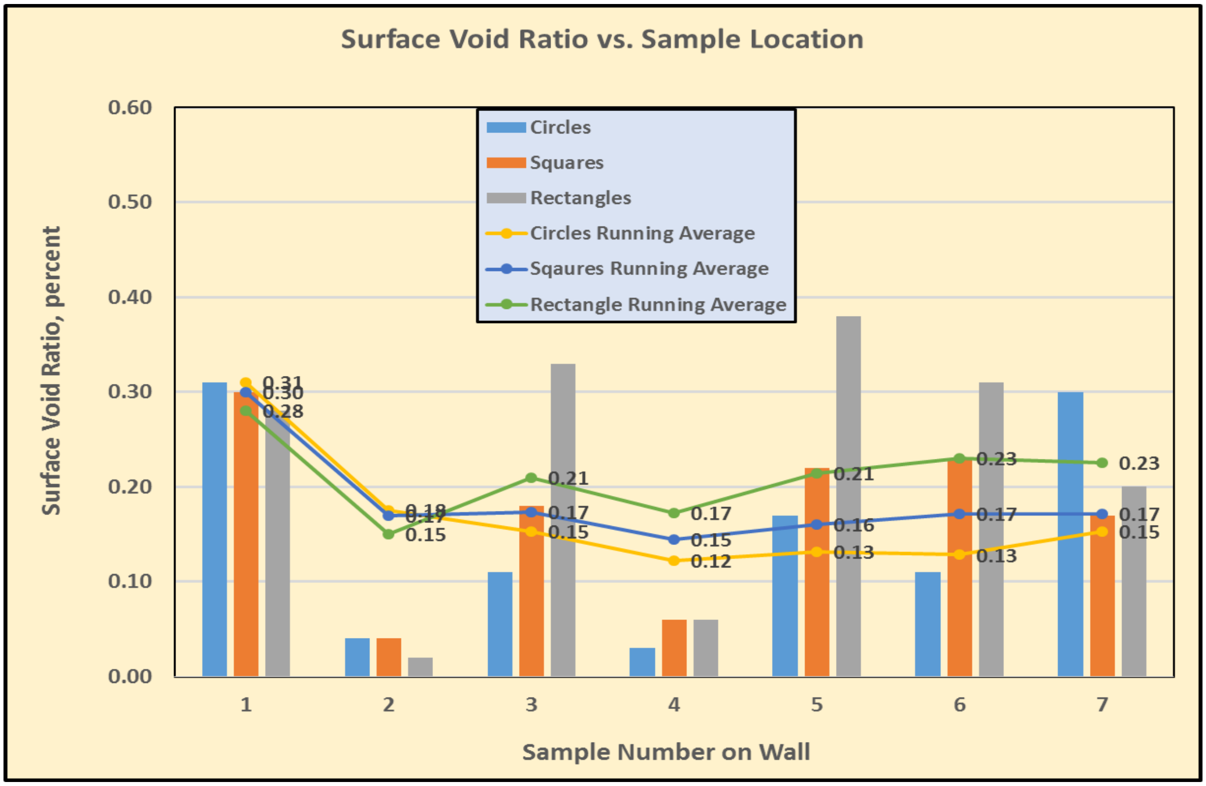


Fig. 6.11 Variations in SVR as affected by sample location, void area measuring method, and several operators (MTSU data for large residential wall)

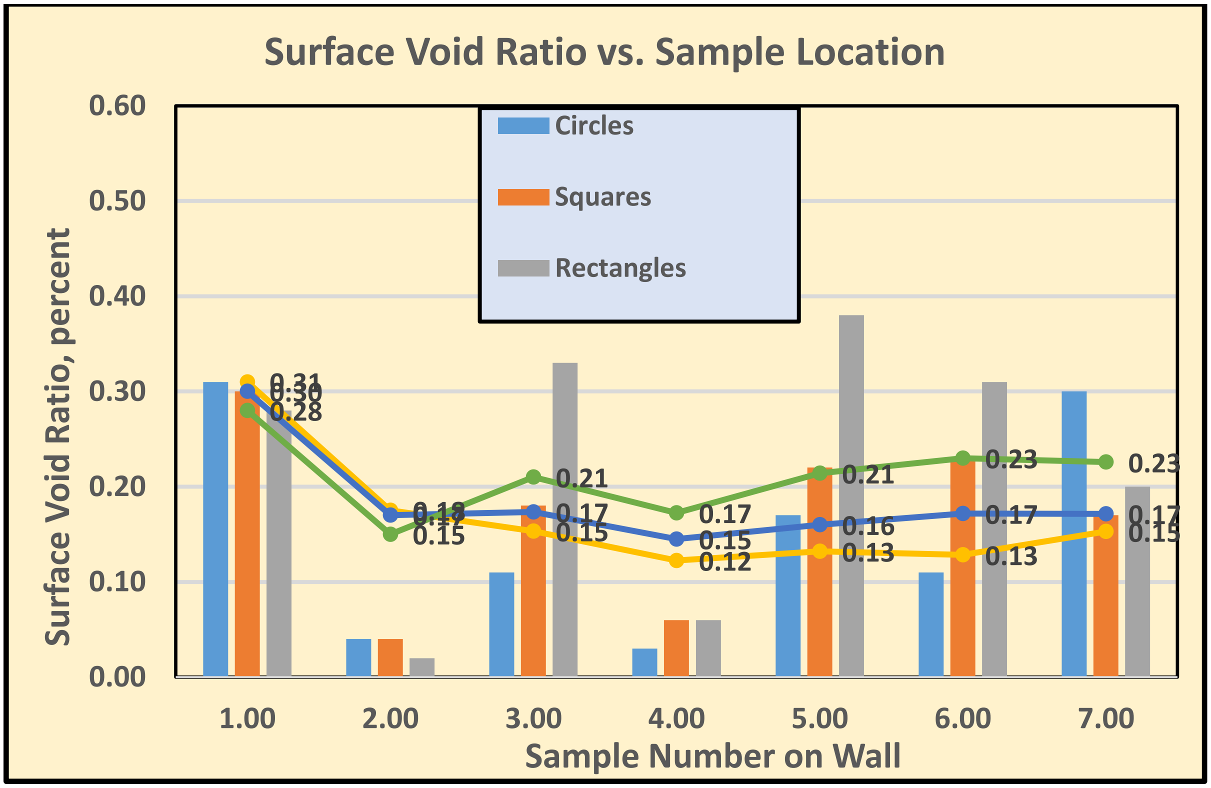


Fig. 6.12 Variations in SVR as affected by sample location, void area measuring method, and several operators (MTSU data for small residential wall)

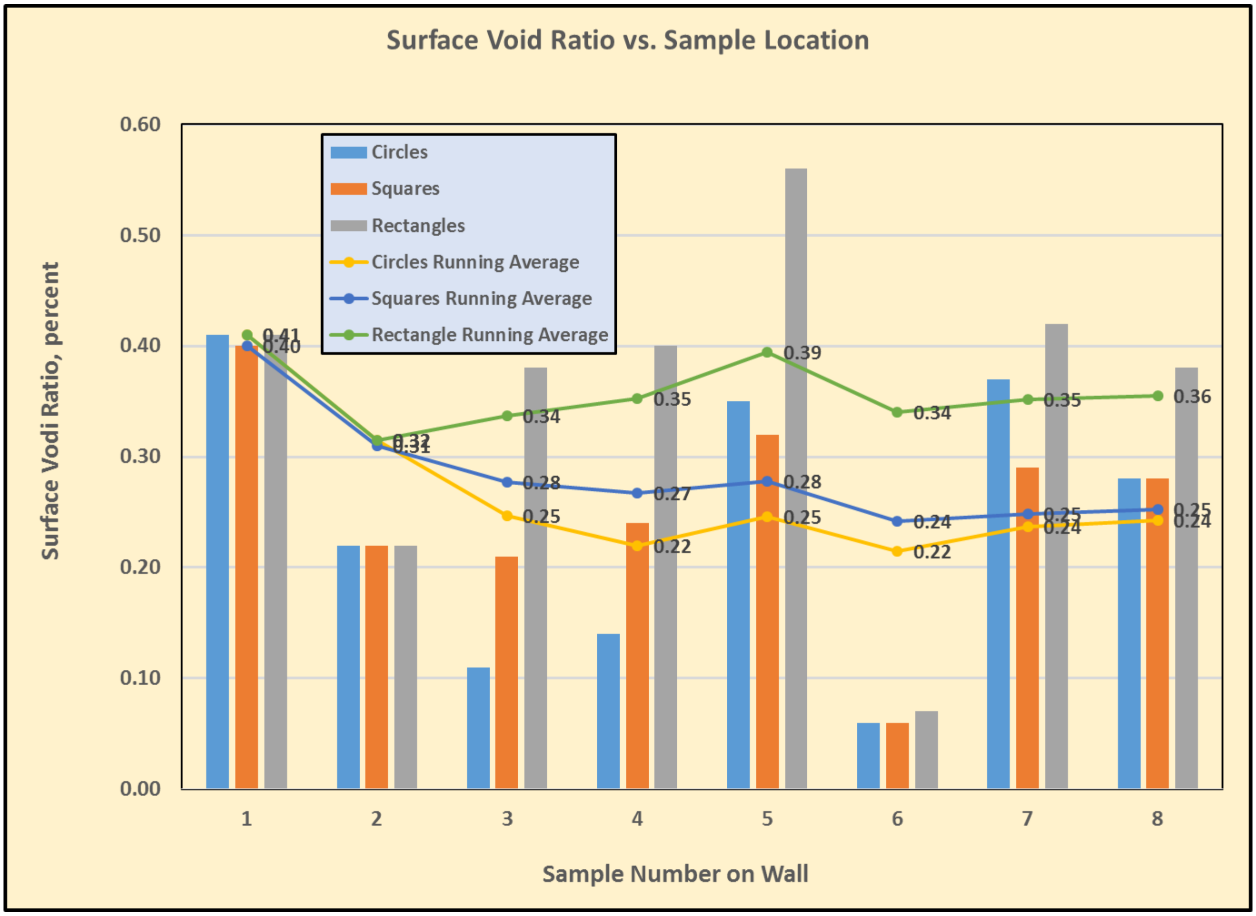


Fig. 6.13 Variations in SVR on parking garage walls measured by MTSU student researchers using three different methods.

Student researchers at NJIT measured SVR on six randomly chosen 2x2-ft samples on a one-placement, 100-ft-long, 15-in.-thick cast-in-place wall on an active construction site in New York City **(Fig. 6.14)**. This wall would have fallen into ACI 347.3R-13 Category CSC2.The 4000-psi air-entrained concrete with a specified 3- to 5-in. slump was pumped into place. Details of the concrete proportions, formwork, release agent, reinforcement, and consolidation procedure are included in Appendix D. Results of the SVR measurements are shown in **Table 6.10 and Fig. 6.15.**

Table 6.10 NJIT Field Measurements of SVR on As-Built Wall

Description	**SVR, %**		
	Circles	Squares	Rectangles
Exposed exterior wall			
Operator 1, Sample 1	2.1	1.3	2.2
Operator 2, Sample 2	1.3	0.43	1.1
Operator 1, Sample 3	0.89	0.54	1.1
Operator 3, Sample 4	0.39	0.26	0.48
Operator 2, Sample 5	1.0	0.39	1.1
Operator 3, Sample 6	0.27	0.18	0.33
Mean,%	1.0	0.5	1.1
Std. Deviation, %	0.7	0.1	0.6
Coef. Of Variation,%	70	20	55
Operator 3, Sample 3 re-do	0.40	0.28	0.43

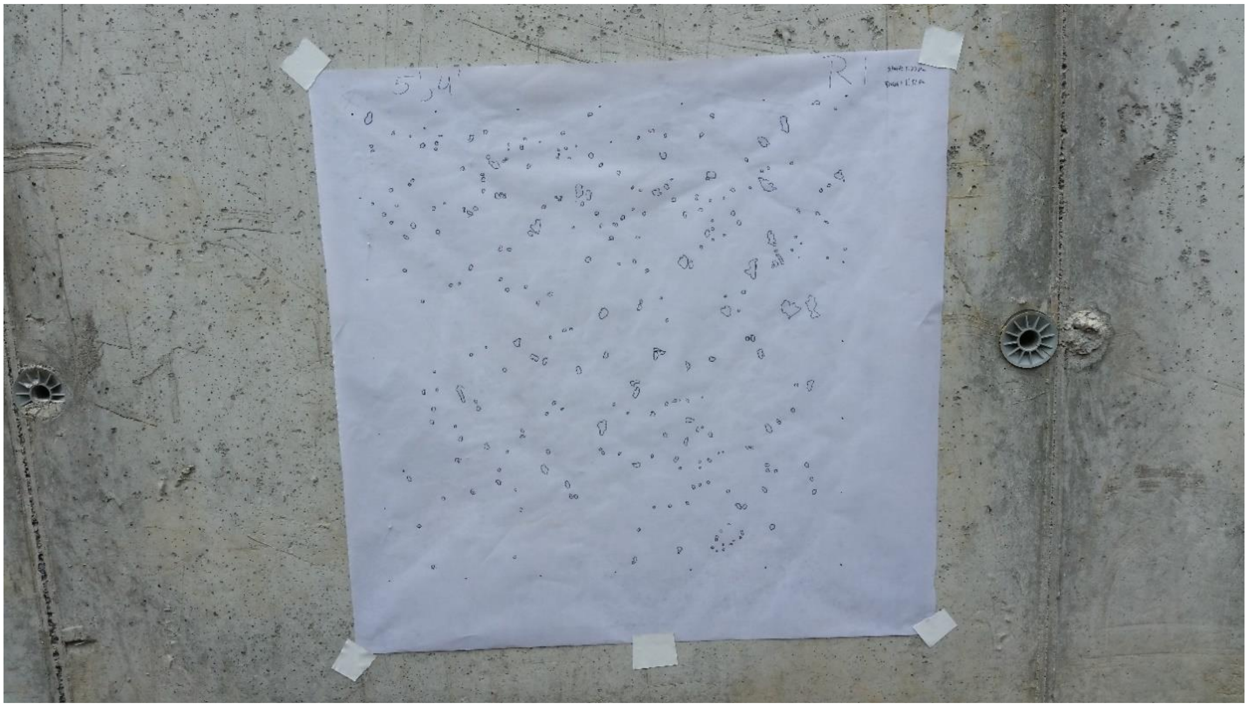


Fig. 6.14 Cast-in-place wall being measured by NJIT student researchers on active construction site

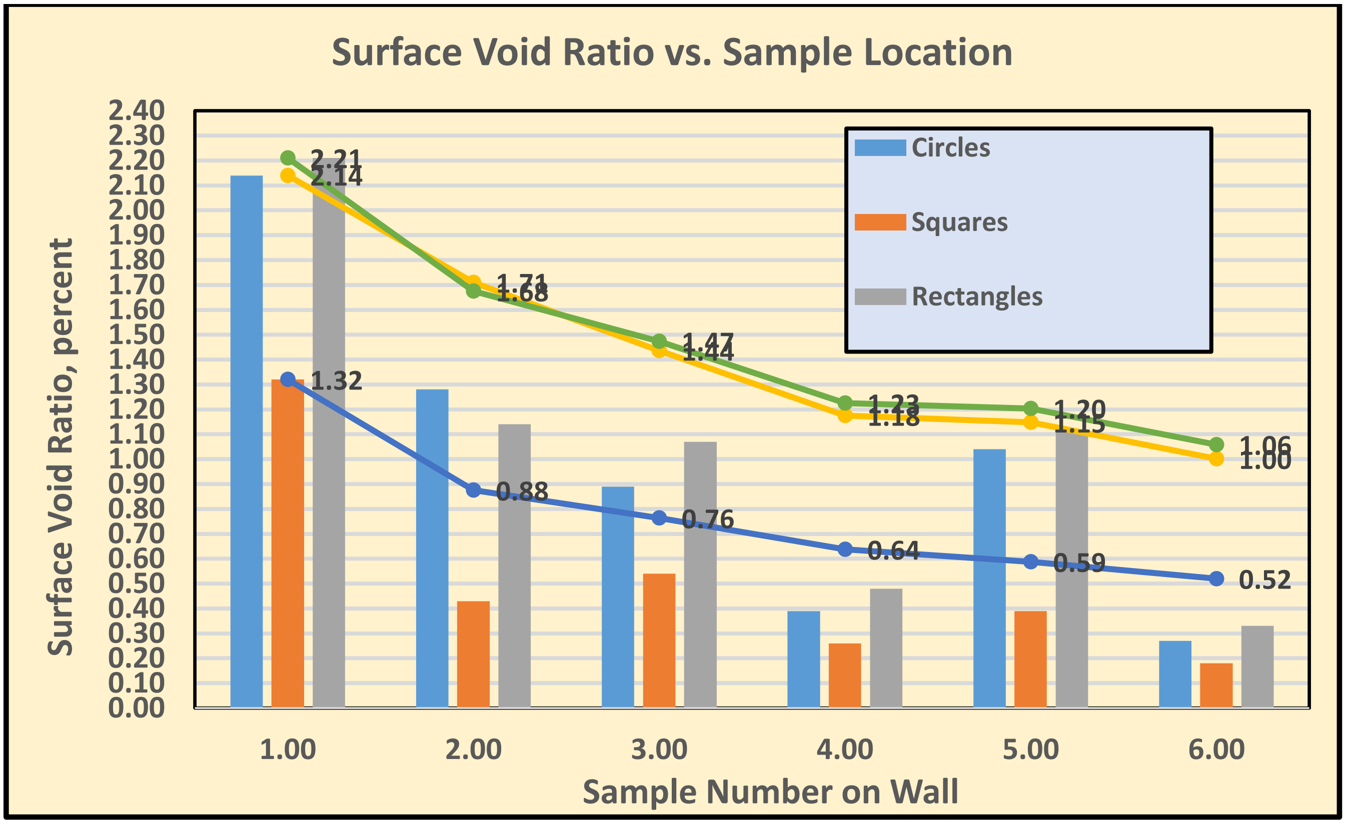


Fig. 6.15 Variation in SVR as affected by randomly chosen NJIT sample location, void area measuring method, and operator

Operator 1 (Samples 1 and 3); Operator 2 (Samples 2 and 5); Operator 3 (Samples 4 and 6)

Student researchers at California State University—Chico chose an existing 25-ft x 8-ft wall and measured SVR on six randomly chosen 2x2-ft samples **(Fig. 6.16)**. Based on the photo, this wall would have fallen into ACI 347.3R-13 Category CSC2. Because this was an existing wall, no details concerning construction were available. Results of the SVR measurements are shown in **Table 6.11 and Fig. 6.17.**

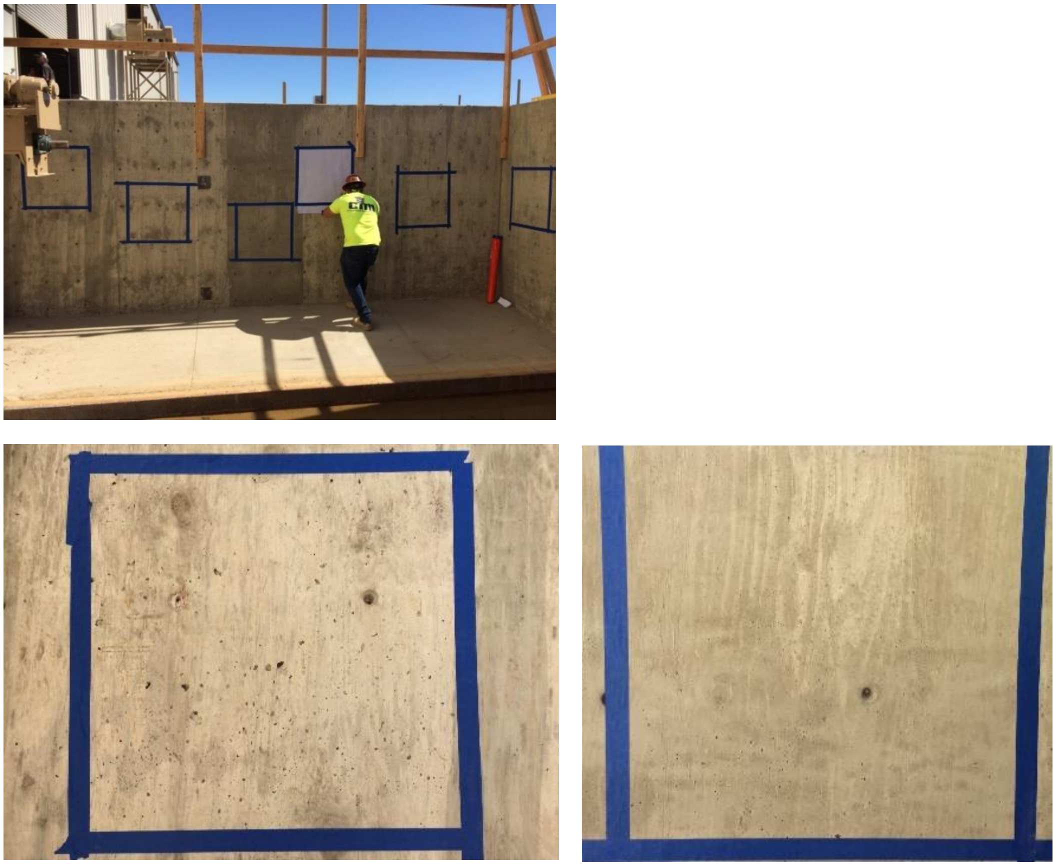


Fig. 6.16 Wall at a warehouse dock measured for SVR by University of California-Chico student researchers

Table 6.11 Chico State Field Measurements of SVR on As-Built Wall

Description	**SVR, %**		
	Circles	Squares	Rectangles
Exposed exterior wall			
Operator 1, Sample 1	0.75	0.63	0.79
Operator 2, Sample 1	0.67	0.68	
Operator 1, Sample 2	0.18	0.15	0.20
Operator 2, Sample 2	0.18	0.15	
Operator 1, Sample 3	0.29	0.27	0.20
Operator 2, Sample 3	0.29	0.31	
Operator 1, Sample 4	0.65	0.58	0.76
Operator 2, Sample 4	0.71	0.67	
Operator 1, Sample 5	0.19	0.17	0.19
Operator 2, Sample 5	0.19	0.15	
Operator 1, Sample 6	0.04	0.05	0.06
Operator 2, Sample 6	0.04	0.05	
Mean,%	0.3	0.3	0.4
Std. Deviation, %	0.3	0.2	0.3
Coef. Of Variation, %	100	67	75

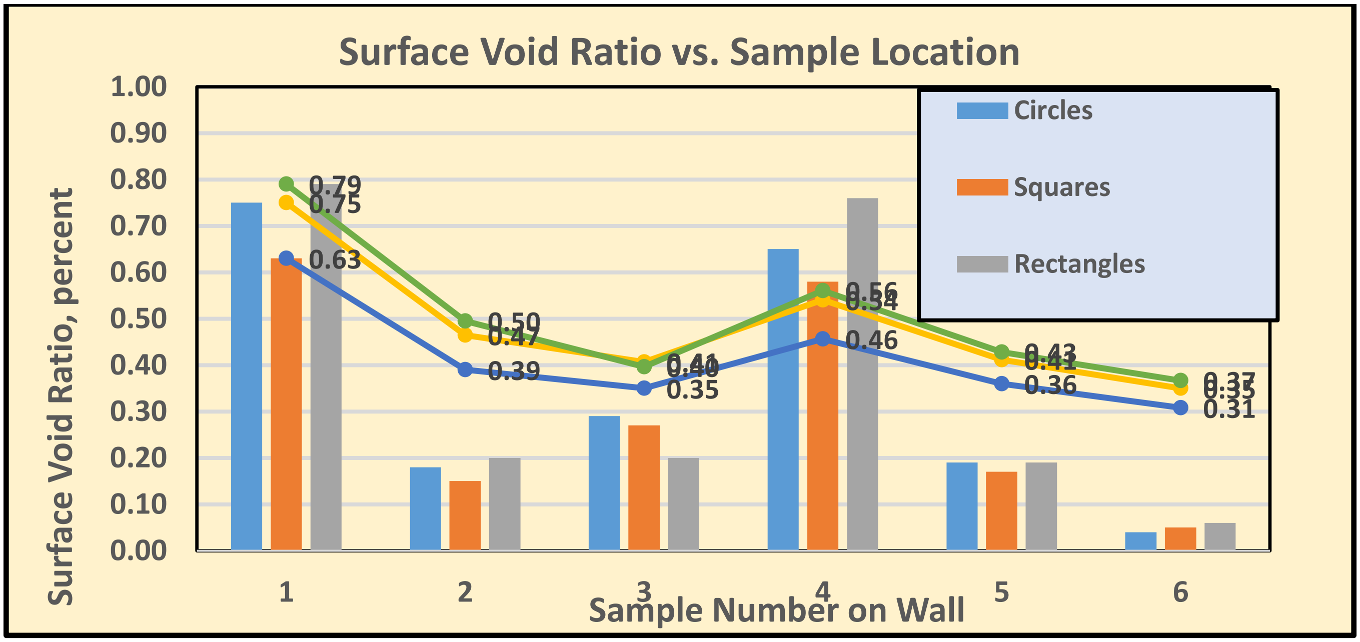


Fig. 6.17 Variation in SVR on Chico State wall as affected by randomly chosen sample locations and void area measuring method (One operator)

Based on these results, if only one sample were chosen to represent a given wall, the wall could fall into two to four concrete surface categories (CSCs) described in ACI 347.3R-13, depending on the three measurement methods used. Thus, the suggestion that one sample be used to characterize a given wall can result in the SVR falling into any three of the four CSC categories.

6.6 SVR measurements made by testing laboratories

In a meeting with a representative of a large German general contractor (see Appendix E), he indicated that the general contractor chooses the sample location for SVR and makes the measurements. No testing laboratory is involved. In the U.S., it's likely that such measurements would be made by a testing laboratory. To gather further data on SVR measurements, requests for proposal were emailed to three testing laboratories serving large cities in Texas, California, and Illinois. Pages 1-3 and 5-7 from ACI 347.3R-13 were attached, and they were asked to provide an SVR determination for existing vertical concrete in their area with an off-the-form finish. The email suggested determining SVR for a wall or column in Categories CSC3 or CSC4 of Table 3.1a as further described in examples of these categories given in Section 3.1 in ACI 347.3R-13. No further instructions were given, but the person contacted was asked to call the principal investigator with any questions. Two of the three labs provided bids without asking any further questions, and a representative from one lab asked for more information before submitting a bid. All three bids were accepted and measurements were made on two walls and a circular column.

Lab A chose a mixed-use condominium complex located in the San Francisco Bay area, outlined one sample with tape, then made the SVR measurements **(Fig. 6.18)**. The calculated SVR was 0.4%, which placed it in the SVR3 category. We inquired about the concrete properties and were told SCC was not used, but received no other information about the concrete mixture.

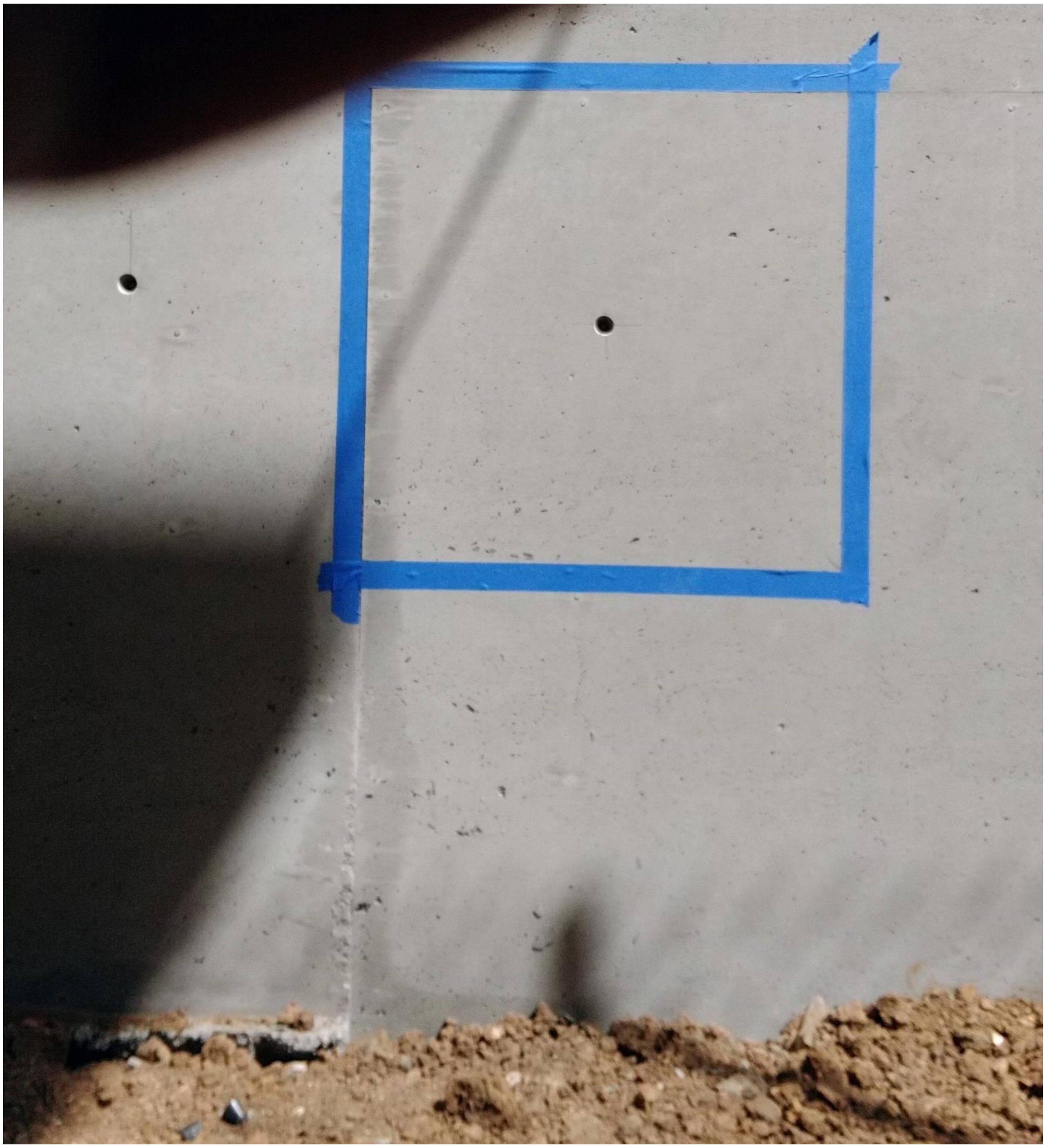


Fig. 6.18 Lab A wall in California condominium project. SVR for one sample = 0.4%

Lab B chose an exposed circular column in a retail-space unit within a Chicago mid-rise building. The sample was chosen as having high visibility at eye level and representative of the overall concrete surface. A 2x2-ft frame was constructed from a rigid thermal plastic roofing membrane that was taped to the column **(Fig. 6.19)**. Voids were measured with a caliper, using the rectangle method, and recorded. Voids with a diameter larger than 3/8 in. were not measured, and voids with an average diameter less than 3/32 in. were excluded from the calculation. Total number of voids was 268. The calculated SVR was 0.4%. In response to an inquiry regarding SCC, the testing lab owner said use of SCC is rare in their market but most concrete contains superplasticizers to produce flowing concrete. Thus, they have stopped using slump measurements and are using slump-spread instead with spreads ranging from 25 to 28 in.

Fig. 6.19 Lab B circular column viewed from 20 ft and close-up of the sampled area. SVR for one sample = 0.4%.

Lab C’s Senior Project Manager called the Principal Investigator for this research project before making any measurements to gather more information. He was told to use the information in the four pages from ACI 347.3R-13, but had questions concerning the methodology. He submitted a two-tier proposal with two different prices: One price was based on the typical way his firm would handle a request for a test unfamiliar to them. An experienced senior technician would be briefed by an engineer on the test method to be used. The technician would then go to the jobsite to measure the voids. SVR would be calculated and the engineer would review the work and write the report. For an additional amount, a letter accompanying the report and written by the Senior Project Manager would describe challenges encountered with testing. The letter would include time required, any additional test data gathered by the Senior Project Manager, and a summary of the data obtained. The two-tier proposal was accepted.

The structure on which measurements were made was a shear wall with an off-the-form finish in the garage portion of a high-rise condominium in Houston **(Fig. 6.20)**. The contractor had been working in the Houston area for 20 years, and the superintendent had worked on eight other similar projects. He said a mixture of new and used forms was used on the project. Because of variations in the size and number of bugholes on the shear wall, the technician couldn’t decide how to choose one sample that was representative of the wall. The Senior Project Manager then went to the jobsite and chose two sample areas—one with a relatively large number of bugholes (Area 1) and one with few bugholes (Area 2) **(Fig. 6.21)**. These samples were about one foot apart. For Area 1, the large number of voids were measured by both the technician and manager using the ACI rectangle method. Time required for the measurements was also recorded. The SVR determined by the technician and manager differed by 0.7% (1.7% vs 2.4%). The rectangle method also took more than an hour for both determinations (75 min. by the manager and 60 min. by the technician). Because of the difference in SVR and time needed for measurement, the manager then decided to determine the SVR of both areas using a different method of measurement. It employed a clear plastic engineering template with square openings of varying sizes **(Fig. 6.22)**. The squares were used in the same manner as the superimposed rectangle method—positioning the template so about as much of the void area fell outside as non-void area fell within the square. The technician and project manager measured both samples using this template method, again recording required time. Results are shown in **Table 6.12.** Note there was closer agreement in SVR and the time required for making the measurements on the Area 1 sample was reduced by at least 50%.

Table 6.12 Comparison of SVR Results on Two Areas by Lab C Using Template with Square Openings

	Area 1 Void A Rea			Area 2 Void Area
Individual	**Time**	**Template**	**Time**	**Template**
Manager	30 min	1.8% (6742.1 mm^2)	15	0.2% (878.2 mm^2)
Technician	30 min	1.6% (6022.2 mm^2)	15	0.2% (710.8 mm^2)

Fig. 6.20 Lab C shear wall with two sample areas taped off for measurement

Fig. 6.21 Sample areas from Lab C shear wall.

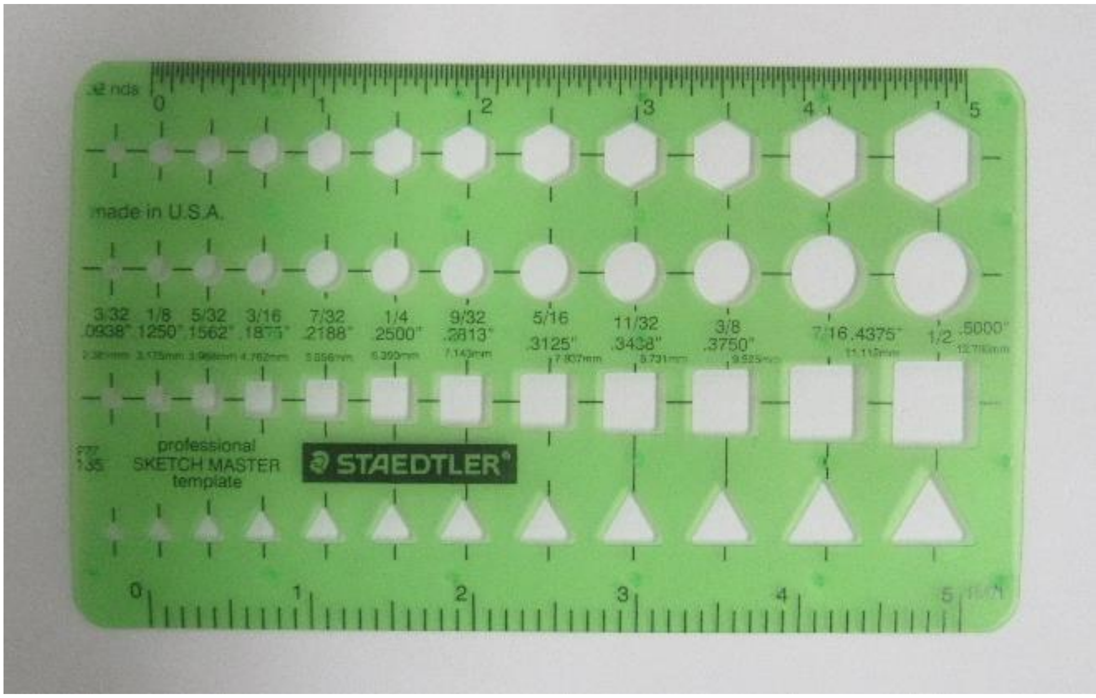


Fig. 6.22 Template with square openings used by Lab C to estimate void area

The initial report resulted in a further conversation between the project investigator and the Senior Project Manager, during which a further series of measurements on the same shear wall was agreed upon. For this series of measurements, three operators (two field technicians and the Senior Project Manage) measured nine samples on the wall **(Fig. 6.23)**. Both field technicians had approximately two years of experience and possess ACI Concrete Field Testing Technician – Grade I Certification. The nine samples were selected (using a random number generator) along the 23-ft long wall up to a height of 8 ft. Specifically, the top-left corner of each sample was determined by randomly generating a number between 24 and 96 for the vertical placement and between 0 and 252 for the horizontal placement. For example, the first location was determined to be 35 in. and 248 in. in the vertical and horizontal directions along the wall, respectively.

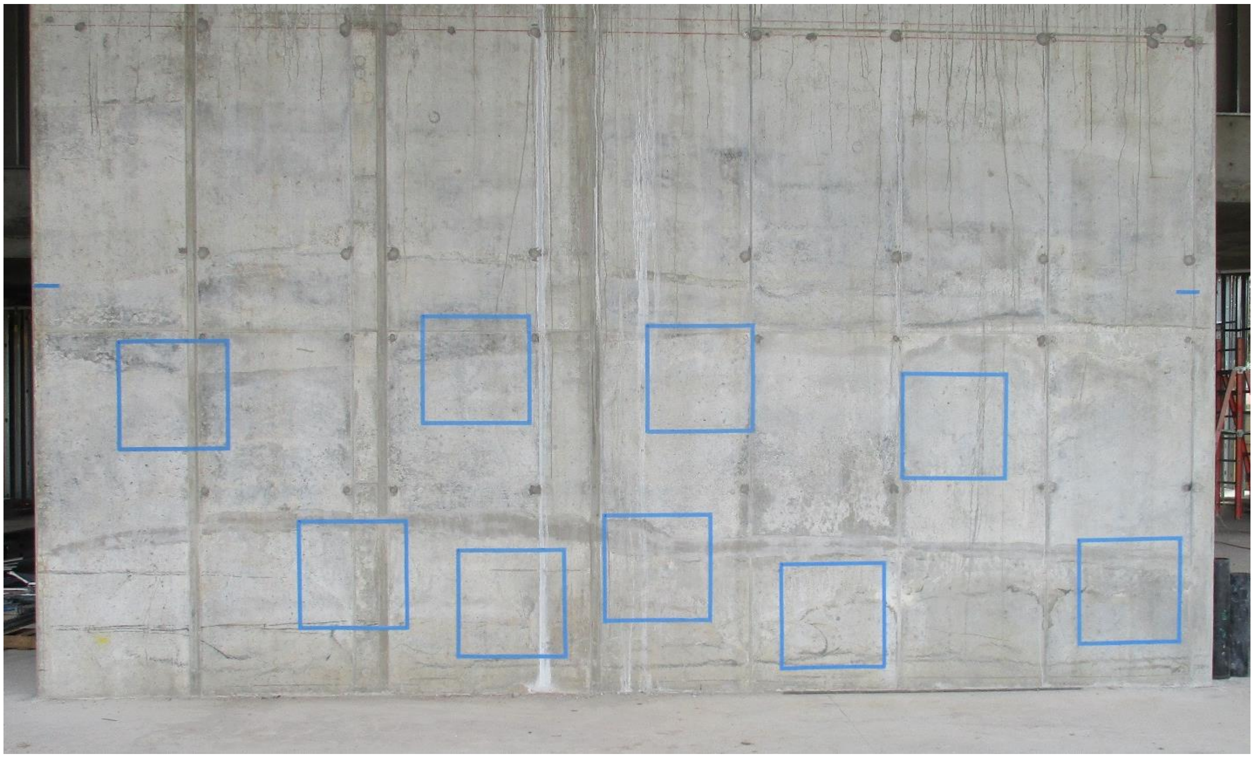


Fig. 6.23 Randomly located samples determined by Lab C for shear wall

Each operator independently identified and measured the individual voids. Measurements were performed in the same order as the locations randomly selected for each sample. Talking among the operators was prohibited to minimize bias in the measurements. As was done previously, a template with square openings was used in a similar manner to the ACI 347.3R-13 rectangle method. **Table 6.13** summarizes the measurements performed by the operators.

Table 6.13 Lab C Mean, standard deviation, and coefficient of variation for three SVR measurements on same sample. Also includes range for each sample and average range.

Sample	**Manager**	**Technician 1**	**Technician 2**	**Range of 3**
Location	Percent Voids (%)	Percent Voids (%)	Percent Voids (%)	
1	0.21	0.19	0.19	0.02
2	0.63	0.57	0.49	0.14
3	0.59	0.51	0.49	0.10
4	1.04	0.94	1.11	0.17
5	0.30	0.37	0.31	0.07
6	0.05	0.06	0.05	0.01
7	0.37	0.41	0.37	0.04
8	0.16	0.21	0.18	0.05
9	0.33	0.31	0.36	0.05
Mean	0.41	0.40	0.39	0.07
Std Dev	0.30	0.26	0.31	
COV	73%	66%	79%	

The SVRs measured by each operator and the running averages were computed and plotted as shown in **Fig. 6.24**, which also includes the ACI 347.3R-13 criteria for the four SVR ranges.

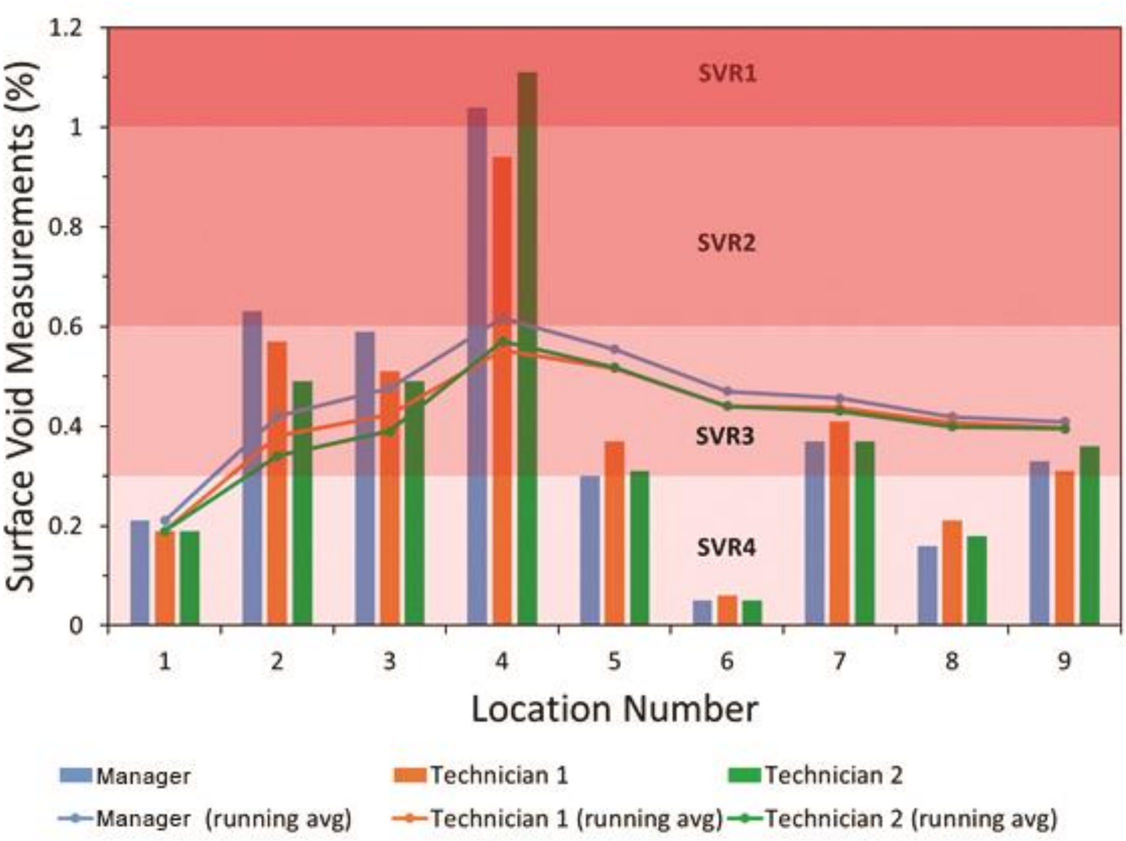


Fig. 6.24 Variation in SVR for Lab C wall as affected by randomly chosen sample locations, and using square openings in template to estimate void area (three operators)

6.7 Summary of SVR measurements on photos and in-place walls

Results of the first sets of SVR measurements made by MTSU student researchers on ASCC photos of walls described in Section 6.1reduced the number of measurement methods to be further used on a test wall at MTSU from six to four: the rectangle, counting squares on graph paper, planimeter, and circle template methods.

As indicated in Section 6.2, there were wide variations in SVR for sample-to-sample testing and within-sample testing (Group A vs. Group B in **Fig. 6.8**) on the test wall built and measured by MTSU student researchers. Based on convergence of the running average, it appeared that six to nine samples were needed for a wall with an average SVR of about 3%.

Measurements on ASCC Photo 4 by other CIM student researchers described in Section 6.3 resulted in an SVR range of 0.9% to 1.3% and required an average time from 17 min. for the counting squares on graph paper method to 26 min. for the rectangle method. The rectangle method was also the most time-consuming of other methods used in this study. Although the counting-squares and circle-template methods consumed less time, the variability from those methods could still result in the SVR for a given photo falling into two or more of the four categories in ACI 347.3R-13.

On ASCC Photo 2 the mean and standard deviations for both the rectangle and counting squares methods were 0.3% and 0.05%, respectively, as indicated in Section 6.4. This means that an entire SVR range of 0.0 to 0.3% (± 3 standard deviation units) is taken up by measurement error. That permits no allowance for variations in SVR due to variations in concrete contractors' materials or methods. The standard deviation for the circle template method used on ASCC Photo 2 was 0.09%, and all three methods used on ASCC Photos 4 and 5 were much larger than 0.3% (**Tables 6.3** through **6.5**). Thus in these cases, with larger SVRs, measurement error exceeded the not-to-exceed SVR range for SVR1 through SVR4.

CIM wall-measurement data in Section 6.5 shows if only one sample were chosen to represent a given wall, the wall could fall into two to four concrete surface categories (CSCs) described in ACI 347.3R-13, depending on the three measurement methods used. Thus, using one sample to characterize a given wall can result in classifying the wall in multiple categories.

As described in Section 6.6, SVR data collected by Labs A and B using the ACI recommended rectangle method fell into the 0.6% maximum SVR range for a category CSC2. Each lab chose one sample location and did not report how the sample was chosen. Nor were they expected to do this because the ACI 347.3R-13 Guide is silent on how to choose a sample location. Because of difficulty in deciding on a "representative" sample, a technician and manager from Lab C chose two samples—with large and small numbers of bugholes. Using the ACI rectangle method resulted in a large discrepancy in the calculated SVR, and also proved to be too time consuming when used on the sample with a large number of bugholes. Because of this the manager decided that measurements made on both samples using a template with square openings were in better agreement and took less time. Further data collected by Lab C was based on measurements made using the template with square openings on nine randomly chosen 2x2-ft samples. The running averages for three individuals making independent measurements converged at about six to nine samples. That is similar to the results from Section 6.1 for the MTSU wall with an average SVR of 3.0% vs. an average SVR of 0.4% for the wall measured by the testing laboratory.

The results from all measurements made by CIM student researchers and testing laboratories indicate that measurement error and the number of samples measured can have a major impact on determination of SVR. Choosing one sample per wall or other formed surface to be evaluated, as suggested in ACI 347.3R-13, is an inaccurate way of representing the wall with respect to bughole size and number.

CHAPTER 7 FACT- FINDING TRIP TO GERMANY

7.1 General description of activities

On June 16, 2016 through June 18, 2016 the principal Investigator visited a MEVA form-manufacturing facility and office complex along with ACI President, Michael Schneider, and ACI Executive Vice President, Ronald Burg. We were accompanied by Rolf Spahr, Sales Director at MEVA and the principal author of ACI 347.3R-13. On June 17, we toured a jobsite of Streib Construction Company where a reinforced concrete frame building expected meet ACI 347.3R-13 Category CSC2 (Normal requirements) was under construction. It is a five-story housing structure with an underground garage. The formwork with nonabsorbent form facing (Alkus) was supplied by MEVA. Category CSC2 is for concrete surfaces where visual appearance is of moderate importance. There were a few formed surface areas on which surface void diameters exceeded about 5/8 in. but they were in areas not exposed to public view. There were also several areas on walls where the number of bugholes seemed excessive and looked to have been patched but in general the surfaces had few bugholes. The surfaces on the exterior walls with what appeared to be excessive bugholes were to be covered with a coating, and thus would not be exposed to public view. No SVR measurements were planned for this structure. Spahr said that when a sample is needed for measuring SVR, the sample location is chosen by the General Contractor, who may or may not self-perform the concrete work.

On the morning of June 17 we heard presentations by MEVA personnel and were given a tour of their manufacturing facilities, facilities for refurbishing forms, and storage areas. In the afternoon, we heard a presentation by Albrecht Obergfell, representative of construction company Wayss & Freytag, Stuttgart, on Experiences/Uses of the German surface guide that was the model for ACI 347.3R-13. He was one of the authors of the 2004 German guide that was the basis for ACI 347.3R-13. Since then, a 2015 revision of the German guide has been published, and is included in the Literature Review discussed in Chapter 5 of this report.

7.2 Questions asked about German use of their document

Prior to the trip, a list of questions had been prepared regarding how the German document is used in Germany. After Obergfell gave his presentation the principal investigator met with him and with Rene Wolleydt of MEVA to get answers to some of these questions. Later, Spahr answered some of the questions and Schneider and Burg attended the discussions. The list of questions that follows was sent prior to the trip. Answers we received are in bold font in the following list. The person answering is represented by asterisks: *Obergfell, **Wolleydt, ***Spahr. The letters “NA” indicate questions not answered as a result of time limitations. Spahr suggested that these questions [I assume not dealing with German practices specifically] be presented to ACI Committee 347. A copy of the report for this visit was sent to the ACI 347 Liaison Committee and Chair McCracken prior to the November 2016 ACI Convention in Philadelphia.
After my return, I asked for a copy of *Merkblatt Sichtbeton Deutscher Beton- und Bautechnik-Verein e.V. 2004*, the German document on which ACI 347.3R-13 is based. Spahr later told me that no copies of the 2004 version were available, but he was able to provide a copy of the 2008 revision.

I requested email addresses for German concrete contractors who speak English. I wanted to ask questions about how they handle specific requirements such as preparing written processes for the successful execution of a project for which the 2004 or 2015 German document is attached to the specifications. Spahr suggested that I ask ACI Committee 347 for their experience in using ACI 347.3R-13. To this date, we have not heard from any U.S. contractors who have built a project for which ACI 347.3R-13 was referenced in the specifications or of any plans and specifications that included a reference to the four concrete surface categories CSC1 through CSC4.

Questions on ACI 347.3R "Guide to Formed Concrete Surfaces"

1. Individuals in the United States are recommending that the ACI 347.3R Guide be incorporated as a specification or to rewrite the Guide in mandatory language and include it as a specification in the Contract Documents. As part of the Contract Documents, contractors would need to provide a bid and complete the work in accordance with the document.

   How is the document used in construction in Germany?
   On what percent of concrete projects is this document used? ***For engineered projects, about 90% of government owned and 70% of private owned. It is not often used for industrial buildings.**
   As a mandatory specification cited by the Architect? ***** The document is attached to the specifications, but is not written in mandatory language. * The contractor says: "Tell me what you want," and the architect uses the document to describe the desired result.**
   As a mandatory requirement cited by the Owner? ***** The document is attached to the specifications, but is not written in mandatory language.**
   How do you adjust your bid if the document is used on the project? **"NA"**
   How does the bid change for each of the four quality levels? ***Bid price increases with increasing quality level.**
   How does the inspection process proceed? **"NA"**

   In the US, for architectural concrete, periodic acceptance is required by ACI 303.1. This document is vague on when and how inspection and acceptance occurs. After each pour? On each section of concrete with the same requirement? At the end of the job? At the end of the one year warranty? ***There are periodic inspections so the contractor can change procedures, if needed, to approximate the desired results. There is no definite time frame for this. If the result of a specific placement is unsatisfactory, the architect or general contractor tells the concrete contractor what the problem is so it can be resolved.**
   How are disputes handled? ****Arbitration, with arbiter being a concrete expert not involved in the project.**

2. Table 3.1a describes the relative costs of different form surface categories, CSC1 through CSC4. The costs are an important factor in determining whether the Owner is willing to pay for the anticipated benefit.
   Can you place a relative number on these costs? For instance if "average" is 1, is very high a factor of 3? ***** The multiplier from the average (1) can be as high as 5. * This multiplier will vary significantly based on reuse of the forms, which is controlled by the shape of the finished structure. A complex shape requiring many one-of-a-kind (single-use) curved form panels will increase the multiplier. Use of white cement, which increases concrete surface color concerns,**

also increases the multiplier. Small monuments are examples of structures for which the multiplier may be very high.

3. If the document is used on the project, contractors will adjust their bid to meet one of the defined four quality levels. Thus the contractor anticipates an inspection and approval process. Two footnotes to Table 3.1a "Description of formed concrete surface categories (CSC)" state (1) "The appearance of the formed concrete surface should only be judged in its entirety, not by looking at separate criteria only. The failure of one agreed criterion according to this guide should not result in the obligation to repair deviations if the overall positive image of the structure or the building is not disturbed." And (2) "The general impression of existing or not existing discolorations can usually be seen only after a longer period of time and for at least 8 weeks. The uniformity of coloring should be judged from the common viewing distance (Chapter 7)."

   How are these two footnotes handled on your projects?
   If the surface must be "judged in its entirety" considering the "overall positive image of the *structure* or *building*", is this handled at the conclusion of the project? *** No. It may be handled when, say, a wall is completely finished. But factors such as time of day when the structure is viewed are important because shadows cause different appearances of the surface.**

   Section 7.2 makes the same point, stating: "This viewing distance allows one to evaluate if the overall appearance of the structure has been achieved" and "The appropriate viewing distance is equal to the distance that allows the entire building, the building's essential parts, or both, to be viewed in their entirety." Is this viewing distance determined at the conclusion of the project? *** Not necessarily. Essential parts, such as exposed walls in a waiting room, will be evaluated when the room is finished, and the appropriate viewing distance will be smaller than the viewing distance for the entire building.**

   If the overall impression of the entire structure or building is not positive, Section 7.1 states that: "Individual criteria should only be judged by the overall appearance of the concrete surface, even if one criterion of the overall grade does not achieve the minimum surface agreed on." If the overall impression of the structure is positive, are measurements of the individual criteria for the defined quality level needed? **No**
   The second footnote indicates that the "general impression" can't be evaluated until at least 8 weeks or longer. This implies the contractor may have a substantial amount of concrete in place prior to finding that it is not acceptable. Is this true? *** Yes. But on many jobs, the contractor can place concrete at other areas on the project where a CSC is not recommended while waiting for the 8 weeks to pass.**

4. The visual examination of the "overall impression" is a major acceptance-rejection point. If the concrete is accepted, the criteria for a defined quality level does not apply. If the concrete is rejected, then the criteria for a defined quality level is evaluated. Visual examination is by definition subjective. The footnotes to Table 3.1b "Description of visible effects on as-cast formed surfaces" state:
   (1) "Color uniformity is subjective and expectations for uniformity should be addressed before construction".

(2) "Concrete color deviations and discolorations cannot be completely eliminated, even using the best practices. If this is a concern, in addition to a mockup use a reference structure of similar size and finish".

(3) "An approved mockup of the surface is required; even the best practices and quality control may result in minor color deviations and discolorations".

The first major acceptance-rejection criterion is the visual examination of the overall impression which is subjective. Then the document states that many individual criteria for a defined quality level are subjective. For instance, determining what are "minor" color deviations or discolorations is subjective.

Because of the subjectivity, why does the document state in the first paragraph that it gives "objective evaluations" for the various levels of formed concrete surfaces? Might this statement confuse the reader? **"NA"**

5. The document states that "Members of the (concrete surface) team can include, but not be limited to, the: d) Formwork supplier, concrete producer, reinforcement and placing and testing lab". This is the only place where testing labs are mentioned in ACI 347.3R-13. What is the role of the testing lab on the concrete surface team? ***A testing lab does not make the measurements related to off-the form surface quality. For instance, if SVRs are measured, the General Contractor chooses the sample location, makes the measurements, and calculates the SVR. When choosing the sample location, the GC should consider the location and visibility of the bugholes. For instance, in the waiting room example, even if there are many bugholes in a location near the floor at one end of the wall, they aren't as visible as the bugholes in the wall just opposite the door to the waiting room. Thus, the sample should be taken at that location, choosing neither the worst nor best looking area.**

Do their personnel make the measurements described in the document Tables, or is that done by the Owner; licensed design professionals; General contractor/construction manager; concrete contractor, special consultants who have expertise in formwork; or the formwork supplier? **As described above, testing labs don't make these measurements.**

Section 6.5, of ACI 347.3R-13 states: "The contractor, with input from the team and consistent with the contract documents, should develop written processes for the successful execution of the project. These processes may include:
a) Execution of mockup requirements;
b) Development, coordination, and review and acceptance of procedures for the formed surface appearance drawing;
c) Concerns to address that will assure the required quality;
d) How to complete surface evaluations;
e) How to make decisions when corrective work will be necessary."

Do German contractors have such written processes and, if so, could we obtain a copy or copies of them, especially the one for "How to complete surface evaluations?" **** German concrete contractors use the document to clarify expectations of the other team members—especially the architect and owner. They want a satisfied architect/owner. Then they produce the written processes.**

What does “How to make decisions when corrective work is necessary” mean? If corrective work is not necessary, how are decisions made differently? **“NA”**

6. Of the 27 surface attribute measurables listed in Tables 3.1b, 3.1c, and 3.1d of ACI 347.3R-13, 15 have a sampling plan if visual examination of the entire surface or panels is considered to be a sampling plan. **[Note:** See Table of this final report, which includes a table listing attributes, whether or not they are measurable, method of measurement, and whether or not there is a sampling plan.**]**

   How are samples chosen for the measurable attributes? *** For SVR, one [presumably] representative sample. No answer was given for other attributes due to lack of time.**

   Who chooses the sample location? *** General Contractor does for SVR. See answer to question 5.**

   If there is more than one sample is the measurable the average value or the maximum value for each sample? For instance, if three samples were used to measure SVR, would 0.3% be the average value for the three samples or each sample must not exceed 0.3%? **“NA”**

   Where there is no measureable method, how are decisions made regarding these attributes, and who makes the decisions? *** The team makes the decision. For CSC3 and CSC4, comparison with a mock-up is often the basis for the decision.**

   [We ran out of time at this point so no answers were given for the remaining questions.]

7. Our work on reproducibility of SVR measurements made on one sample, and using several methods, indicates that variability due to measurement error can result in one sample falling within three of the four ranges given for Formed Surface Categories CSC1 through CSC4. This testing variability is so great that it would allow contractors no variability in the quality their workmanship. Yet we know that variability in workmanship occurs on every project, as evidenced by the need for achievable tolerances.
   - Has reproducibility of the “rectangle method” for SVR been evaluated in Germany? If so, what were the results?
   - If there is a “failing” SVR test result, are retests permitted?

8. In ACI 347.3R-13, the results for Surface Void Ratio (SVR) are apparently based on measurements made on one 2x2-ft-square sample. The choice of that sample location is critical to SVR that is determined. Our work using several samples, chosen randomly, and spread across a wall indicates a wide variation in SVR from one sample to the next.
   - Who determines the sample location, and on what basis? Is that covered in the written processes mentioned above?
   - Why was the decision made to use only one sample for a given section of wall?

9. ACI 347.3R-13 gives little guidance in controlling SVR to produce Formed Surface Categories CSC1 through CSC4. We believe the U.S. contractor might have little idea as to what is required for each category.

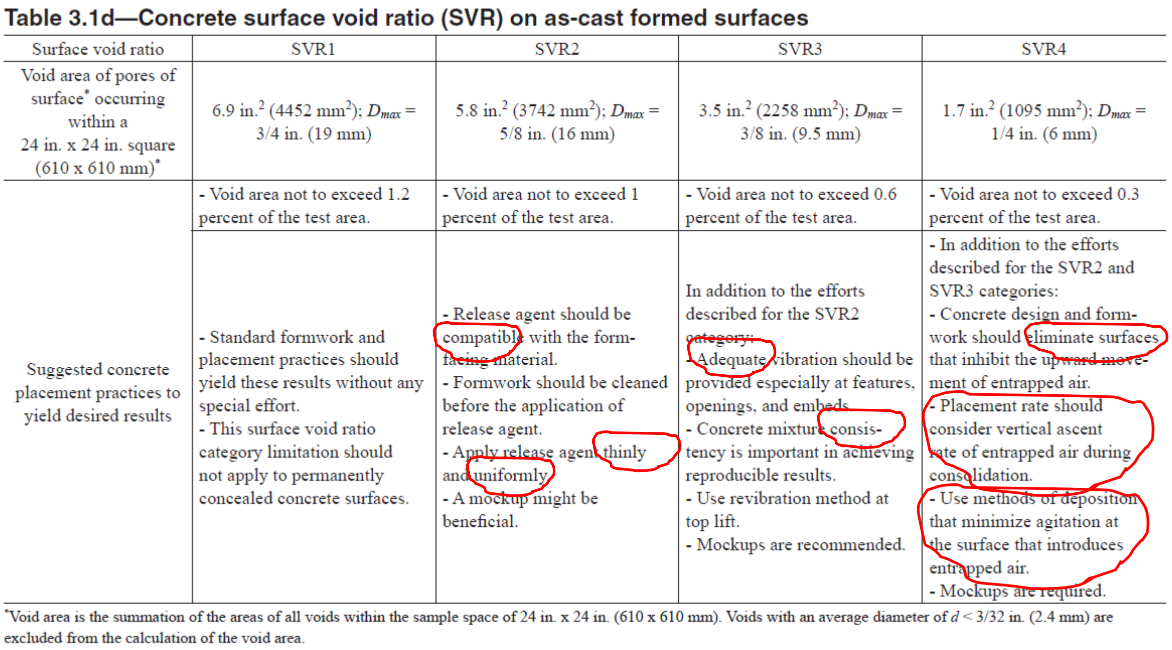


Table 3.1d—Concrete surface void ratio (SVR) on as-cast formed surfaces

Surface void ratio	SVR1	SVR2	SVR3	SVR4
Void area of pores of surface* occurring within a 24 in. x 24 in. square (610 x 610 mm)*	6.9 in.^{2} (4452 mm^2); D_{max} = 3/4 in. (19 mm)	5.8 in.^{2} (3742 mm^2); D_{max} = 5/8 in. (16 mm)	3.5 in.^{2} (2258 mm^2); D_{max} = 3/8 in. (9.5 mm)	1.7 in.^{2} (1095 mm^2); D_{max} = 1/4 in. (6 mm)
Suggested concrete placement practices to yield desired results	- Void area not to exceed 1.2 percent of the test area.	- Void area not to exceed 1 percent of the test area.	- Void area not to exceed 0.6 percent of the test area.	- Void area not to exceed 0.3 percent of the test area.
	- Standard formwork and placement practices should yield these results without any special effort. - This surface void ratio category limitation should not apply to permanently concealed concrete surfaces.	- Release agent should be compatible with the form-facing material. - Formwork should be cleaned before the application of release agent. - Apply release agent thinly and uniformly. - A mockup might be beneficial.	In addition to the efforts described for the SVR2 category: - Adequate vibration should be provided especially at features, openings, and embeds. - Concrete mixture consistency is important in achieving reproducible results. - Use revibration method at top lift. - Mockups are recommended.	- In addition to the efforts described for the SVR2 and SVR3 categories: - Concrete design and formwork should eliminate surfaces that inhibit the upward movement of entrapped air. - Placement rate should consider vertical ascent rate of entrapped air during consolidation. - Use methods of deposition that minimize agitation at the surface that introduces entrapped air. - Mockups are required.

*Void area is the summation of the areas of all voids within the sample space of 24 in. x 24 in. (610 x 610 mm). Voids with an average diameter of d < 3/32 in. (2.4 mm) are excluded from the calculation of the void area.

Some of the circled suggestions are either vague or confusing. What do they mean?

- If a German contractor is given a specification requiring a Formed Surface Category of CSC3 for walls, how do his construction methods differ from those for a CSC2 wall—with special emphasis on requirements for color and SVR?
- Does the contractor use film surface thickness gages to measure the proper application of form release agents? Is this done throughout the project?
- Our literature review on surface porosity (bugholes) includes many different suggestions for proportioning concrete mixtures to reduce the size and frequency of bugholes. But some of the suggestions are contradictory. How does the contractor choose the proper concrete mixture that will reduce SVR?

10. In our literature review, we found several other rating systems for surface porosity, but most were less stringent than the SVR values given in ACI 347.3R-13.
    - How were the SCR values of 0.3%, 0.6%, 1.0%, and 1.2% chosen? Were they based on measurements made in the field? If so, how many measurements were made?

CHAPTER 8 CONCLUSIONS

The Introduction to ACI 347.3R-13 states that the document will correct a lack of uniformity in the appearance criteria of concrete surfaces by providing definitions for various levels of formed concrete surfaces, and giving objective evaluations of them. A review of the document shows that although there are some objective criteria for evaluation, the primary determinant of acceptance is the entire impression of the surface meeting the contract expectation. This creates two problems:

- The entire impression is subjective.
- In Germany, the contract expectation is determined by citing in the specification the desired concrete surface category referenced in their Guide, which is included in the bid package. Their document is not written in mandatory language and, in *Specifications for Structural Concrete* (ACI 301), reference to non-mandatory documents is not permitted. Thus specifiers must include all of the recommendations in ACI 347.3R-13, written in mandatory language, if they require a surface category (CSC) described in that document. That is discouraged in this report for reasons that follow.

Vague and undefined terms in ACI 347.3R-13 can cause confusion and conflicts during construction. In many bidding situations, contractors don't have an opportunity to clarify the as-built concrete surface requirements and have only the option to strike these requirements in their bid. Using that option often disqualifies their bid, but failure to strike them increases their risk.

The complexity of the CSC recommendations seems unnecessary for what the document calls basic or normal categories. Using these recommendations for basement walls, electrical or mechanical rooms, or stairwells in non-architectural concrete—as is suggested in ACI 347.3R-13—is in excess of what is needed for acceptable performance for most such applications of concrete. For bugholes or fins in formed concrete basement walls that will receive spray-on waterproofing coatings or be painted, grinding the fins and rubbing the surface with a cement-sand grout may be needed to prevent holidays in these coatings. But such treatments still don't need to have any color uniformity requirements because the walls will be covered, and don't qualify as off-the-form finishes.

In this research, measurements of SVR on both photos and formed surfaces of existing cast-in-place concrete walls indicate that values ranging from SVR1 through SVR4 are achievable, but this is dependent on precision of the measurement and, more importantly, sample size. ACI 347.3R-13 implies that one 2x2-ft sample on a structural unit to be evaluated is adequate. If the term "sample" means instead, a number of randomly selected sub-sample locations, the data indicates that the needed number would range from at least three to nine to result in a representative value for SVR. The average range of values among three operators using the same area measurement methods (See Table 6.13) also indicates the need for more than one sample location. Use of one "representative sample" (no sub-samples), as indicated in the German document that is the basis for ACI 347.3R-13, could place the surface being measured into any of the four SVR categories. Choice of a one-sample location is also a subjective decision.

There is also no indication, in our data or literature search, concerning the specific steps needed to achieve the maximum SVR values recommended in ACI 347.3R. The measurements made by a testing laboratory on a shear wall within an 8-ft. by 23-ft. area (See Chapter 6) indicates that this was placed by a contractor using concrete produced by one supplier and with similar placing and consolidation methods. There was a mixture of new and used forms as might be expected on most non-architectural concrete projects. Yet depending on the number of locations used for samples, the wall could have fallen into any of three SVR classifications. That is also true for other walls measured in this research.

Section 5.1 of ACI 347.3R-13 states the following:
"Before writing specifications, the licensed design professional should determine the desired appearance of the concrete surfaces and which design features the contract documents should describe. In the contract documents, the licensed design professional chooses the desired CSC from Table 3.1a and specifies the expected appearance and features for each specific area. The contractor, therefore, can determine the means and methods, material type and quantities, and associated costs to achieve the specified concrete surface finish. The literature review summarized in Chapter 5 of this report, however, indicates that determining means and methods for producing a given SVR has not been adequately described because:

- The SVR maximum limits--from 0.3% to 1.2% for the highest to lowest surface quality, respectively, are not based on any data presented in ACI 347.3R-13. **Linder (1992, Part 2)** refers to an Austrian article [Huber, G.: Sichtbeton, Hersusgeber: Verein der osterr. Zementtabrikanten, Wien 1979] suggesting that: "On a test surface of at least 50 x 50 cm^2 a content of 0.3 percent of pores above 1 mm diameter on the test surface is regarded as realistic." At the extremes, **Ozkul and Kucuk (2011)** stated that "In most cases, reducing the surface void area contributed by the bugholes to 1% is considered a successful goal in bugholes reduction." **Anon 2015** and **Anon,** *A Guide to Specifying Visual Concrete,* states that "blowholes are permissible up to a max. size of (3 mm); their number may not exceed (10) in any square metre." The values in parentheses appear to be default values, but the default would result in a very low maximum SVR of 0.07% assuming all were 3mm in size. In all instances, no data were cited to validate the SVR values suggested.
- There are many variables affecting the size, number, and concentration of bugholes.
- There are disagreements on the effects of the variables—SVR increases or decreases with a given change in some of the variables.

This increases risk for the contractor. While there is some agreement that permeable form liners or self-consolidating concrete can significantly reduce the size and number of bugholes, neither of these methods is without some downside. Permeable forms significantly increase cost because they can't be reused, and do not produce the fair-faced appearance targeted in ACI 347.3R-13. Use of self-consolidating concrete increases concrete costs and also increases the need for very tight quality control in order to produce the desired SVR. It's doubtful that the cost using SCC can be justified in many cases for the basic or normal concrete surface categories described in ACI 347.3R-13.

Based on what was learned in the trip to Germany, their procedure for utilizing the German document could not be applied in the U.S. Simply attaching a copy of ACI 347.3R-13 to the contract, and requiring specific concrete surface categories as indicated on the drawings, in essence makes ACI 347.3R-13 part of the specification. But ACI Guides are not written in mandatory language, and changing the language to a mandatory form, as is suggested in both the document and ACI SP-4, would require numerous changes in language that is not clear enough for a specification.

CHAPTER 9 RECOMMENDATIONS TO ACI COMMITTEE 347 FOR REVISING ACI 347.3R-13”

- Consider the comments in Appendix B, Review of ACI 347.3R-13, when revising the document.
- State in the Synopsis and Introduction that this document is intended to allow concrete producers and contractors to discuss and clearly understand expectations of the Owner and Licensed Design Professional, but is not a part of the contract documents.
- Do not suggest including ACI 347.3R-13 as part of the bid package or converting the document to a specification. Also eliminate mandatory language such as use of the word “requirements” in the Guide.
- Eliminate the CSC requirements for Surface Void Ratio and Color Uniformity until a sampling plan and standardized measurement method can be developed to show, based on test data, that any classifications for these two properties are clearly differentiated and can be consistently produced.
- Consider working jointly with ACI Committee 303 to make this a Guide to Formed Architectural Concrete Surfaces, thus limiting the scope and eliminating the recommendations for basic and normal concrete as defined in ACI 347.3R-13.
- Sponsor research through the ACI Concrete Research Council or other funding body to provide data that will enable contractors and concrete producers to achieve quality levels meeting the recommendations for Concrete Surface Categories described in the document.

APPENDIX A

ACI 347.3R-13

Guide to Formed Concrete Surfaces

Reported by ACI Committee 347

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The primary goal of the construction team is to produce as-cast concrete surfaces that meet project specifications and expectations. Although various descriptions, interpretations, and methods exist to achieve an as-cast concrete surface, no unified definitions of different concrete surfaces exist.

This document defines four quality levels of formed concrete surfaces and provides methods to achieve and evaluate them. These quality levels are identified by three surface finish categories: 1) form facing; 2) concrete surface void ratio; and 3) characteristics of form-facing materials. The basic procedures for classification are defined using tables derived from recommendations of the German Concrete Association (DBV) (Merkblatt Sichtbeton Deutscher Beton- und Bautechnik-Verein e.V. 2004).

This guide assists the project owner, design team, contractor, formwork and concrete suppliers, and all other parties in reaching a more specific understanding of how to produce a more clearly defined as-cast concrete surface. All other parties should understand the procedures, processes, and costs for producing defined surfaces of formed concrete. The guide also discusses all phases of construction relating to concrete surfaces from planning, description of work, and construction through acceptance of a concrete surface.

This guide can be used by both specifier (architect/licensed design professional) and contractor as a supplemental tool for defining, specifying, and evaluating concrete surfaces and offers guidance to the development of concrete surface specifications and expectations. Please refer to ACI 303R-12 for information regarding post-construction treatment of formed concrete surfaces.

This guide also describes an entire process for comprehensive use, including the creation of a concrete surface team and its defined roles and responsibilities in the construction process.

Keywords: color uniformity; exposed to view; form facing; job-built formwork; mockup; offsets; panelized formwork; reference area; surface finish; surface void ratio; texture; tolerances.

CONTENTS

ACI 347.3R-13 was adopted and published January 2014.

Table 3.1a—Description of formed concrete surface categories (CSC)

CHAPTER 1—INTRODUCTION

The scope of this guide is to solve a lack of uniformity in the appearance criteria of concrete surfaces, provide definitions for the various levels of formed concrete surfaces, and give objective evaluations of them.

Although there are various reference sources for constructing and evaluating concrete surfaces, none exist that offer a comprehensive guidance and understanding to its production and evaluation. Several ACI and ASCC documents, however, do provide partial guidance:

1) ACI 347-04 provides terms for classes of formed concrete surfaces, discusses irregularities in formed surfaces, and gives general guidance for the use of formwork for concrete;

2) ACI 309R-05 provides terms about visible effects of consolidation on formed concrete surfaces, why they occur, and how to avoid them;

3) ACI 303R-12 discusses architectural concrete, applications, and details of production including formwork, release agents, repair, and economics;

4) ACI 301-10 specifies concrete surfaces (Section 5.3.3.3);

5) The ASCC Education and Training Committee (1999) guide uses samples of concrete surfaces to illustrate appearance expectations.

These references, which exclude uniform appearance criteria or a process for evaluating formed concrete surfaces, make it difficult to achieve a wide range of expectations.

The ultimate authority on a project is the contract document. The contract document is a guide for the:

a) Designer to specify the desired surface finish;

b) Owner to understand what the final product will approximately look like;

c) Contractor to select facing materials, concrete mixture, release agents, and construction methods to achieve the specified surface finish.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://www.concrete.org/Tools/ConcreteTerminology.aspx. Definitions provided herein complement that source.

area exposed to view—portion of structure that can be observed by the public during normal use.

blushing—slight pink or rose color on concrete surface.

flatness—deviation of a surface from a plane.

form facing—the form material that comes in direct contact with the concrete.

gap—space between abutting edges of the form-facing materials measured on the plane of the form surface.

mockup—a sample of a component of the building as specified in the contract documents that is used to establish the expected surface finish.

reference area—a significantly large area of a completed concrete surface serving as a basis of comparison for the acceptance of a surface category of work at a specified location of a given project.

surface void ratio—the ratio of the total surface void area to the total concrete surface area after stripping with no subsequent surface treatment.

CHAPTER 3—FORMED CONCRETE SURFACE DESCRIPTIONS

3.1—General

Tables 3.1a through 3.1d define the various measurable properties pertaining to formed concrete surface texture, surface void ratio, color, flatness, and joints. Four concrete surface categories (CSCs) are defined in Table 3.1a. CSC1 has the lowest classifications and CSC4 the highest for a finished surface. The individual constituents used to define each CSC are further described in Table 3.1b. The classification for form-facing materials is described in Table 3.1c. The surface void ratio is defined and categorized according to net pore area in Table 3.1d.

Concrete surface levels are specified for individual parts of the structure to reflect the owner's needs, desires, and budget. Possible examples include:

a) Basement walls: CSC1;

b) Industrial structures: CSC1 or CSC2;

c) Electrical and mechanical rooms: CSC1 or CSC2;

d) Stairwells: CSC1, CSC2, or CSC3;

e) Commercial building exteriors: CSC3;

f) High-end commercial building exteriors: CSC3 or CSC4;

g) Religious structures or museums: CSC3 or CSC4;

h) Monumental or landmark structures: CSC4.

These examples are only provided to illustrate the various classifications of concrete surfaces and are not recommendations of the committee.

Concrete surface finish schedules should be designated as part of the contract documents in drawings or by designations on exterior/interior views of the structure.

Table 3.1a—Description of formed concrete surface categories (CSC)

Formed concrete surface category[*]			Description	CSC requirements[†‡]					Additional requirements				Relative costs
				Texture	Surface void ratio[§]		Color uniformity[‖]		Surface irregularities	Construction and facing-joint	Mockup#	Form-facing category[**]	
					a	na	a	na					
Concrete surface finish with	Basic requirements	CSC1	Concrete surfaces in areas with low visibility or of limited importance with regard to formed concrete surface requirements, used or covered with subsequent finish materials.	T1	SVR1	SVR1	CU1	CU1	SI1	CJ1	Optional	FC1	Low
	Normal requirements	CSC2	Concrete surfaces where visual appearance is of moderate importance.	T2	SVR2	SVR1	CU1	CU1	SI2	CJ2	Optional	FC1	Average
	Special requirements	CSC3	Concrete surfaces that are in public view or where appearance is important, such as exterior or interior exposed building elements.	T3	SVR3	SVR2	CU2	CU2	SI3	CJ3	Highly recommended	FC2	High
		CSC4	Concrete surfaces where the exposed concrete is a prominent feature of the completed structure or visual appearance is important.	T4	SVR4	SVR3	CU2	CU3	SI4	CJ4	Should be required	FC3	Very high

[*] For matching requirements of formed concrete surface categories, please refer to the following notes and tables.

[†] The appearance of the formed concrete surface should only be judged in its entirety, not by looking at separate criteria only. The failure of one agreed criterion according to this guide should not result in the obligation to repair deviations if the overall positive image of the structure or the building is not disturbed.

[‡] These requirements/features are described in detail in Table 3.1b.

[§] Void area of pores of surface. Refer to Table 3.1d; legend: a = absorbent form facing; and na = nonabsorbent form facing.

[‖] The general impression of existing or not existing discolorations can usually be seen only after a longer period of time and for at least 8 weeks. The uniformity of coloring should be judged from the common viewing distance (Chapter 7).

[#] If required, additional mockups should be prepared.

[**] Refer to Table 3.1c.

Table 3.1a—Description of formed concrete surface categories (CSC)

Table 3.1b—Description of visible effects on as-cast formed surface

Criterion	Classification	Characteristics
Texture, panel-joint[*]	T1 (Table 4.6.4)	- Acceptable gaps in adjacent formwork components ≤ 3/4 in. (19 mm) (6.1 h). - Acceptable depth of mortar loss ≤ 1/2 in. (13 mm). - Acceptable surface offsets of panel joints up to 1 in. (25 mm). (ACI 117-10, Section 4.8.3, Class D). - Allowable projections 1 in. (25 mm) from adjacent surface. (ACI 301-10, Section 5.3.3.3.a). - Form-facing material examples: Rough sawn lumber, CDX plywood, and particle board. - Imprints of modular panel frames are acceptable.
	T2 (Table 4.6.4)	- Acceptable gaps in adjacent formwork components ≤ 1/2 in. (13 mm) (6.1 j). - Acceptable depth of mortar loss ≤ 3/8 in. (10 mm). - Acceptable surface offsets of panel joints up to 1/2 in. (13 mm) (ACI 117-10, Section 4.8.3, Class C). - Allowable projections 1/2 in. (13 mm) from adjacent surface. - Form-facing material examples: Class BBOES plywood, MDO plywood. - Imprints of modular panel frames are acceptable.
	T3 (Table 4.6.4)	- Acceptable gaps in adjacent formwork components ≤ 1/4 in. (6 mm) (6.1 j). - Acceptable depth of mortar loss ≤ 1/4 in. (6 mm). - Acceptable surface offsets of panel joints up to 1/4 in. (6 mm) (ACI 117-10, Section 4.8.3, Class B). - Allowable projections 1/4 in. (6 mm) from adjacent surface (ACI 301-10, Section 5.3.3.3.b). - Form-facing material examples: HDO plywood, phenolic surface film, plastic, or steel. - Imprints of modular panel frames are acceptable.
	T4 (Table 4.6.4)	- Formwork should be grout tight. Avoid grout/mortar leakage and correct where occurs. - Permissible surface offsets of panel joints up to 1/8 in. (3 mm) (ACI 117-10, Section 4.8.3, Class A). - Form-facing material examples: HDO plywood, PSF plywood, full plastic, steel, and fiberglass. -Imprints of modular panel frames are unacceptable unless demonstrated and approved in the mockup.
Surface void ratio (SVR)	SVR1-SVR4	- Refer to Table 3.1d.
Color uniformity[†]	CU1	- Light and dark color variations are acceptable. - Color variations between adjacent placements and layer lines are acceptable. - Rust and dirt stains are acceptable.
	CU2	- Gradual light and dark discolorations are acceptable. - Color consistency between adjacent placements and layer lines should be mostly uniform.[‡] - Concrete source materials and form-facing material should be of consistent type, grade, and source to avoid causing deviations in appearance. - Rust and dirt stains are unacceptable.
	CU3	- Discolorations caused by concrete source material of different type and origin; different types or treatments of facing materials; or inconsistent treatment of concrete surfaces are unacceptable.[§] - Rust stains, dirt stains and visible pouring layers are unacceptable.
Surface irregularities[‖]	SI1	- ACI 117-10, Section 4.8.3, Class D-Surface. - Maximum gradual deviation over a distance of 5 ft (152 cm), or abrupt deviation is 1 in. (25 mm). - Limit deflection of formwork structure to $L/240$. - ACI 117-10, Section 4.8.2 does not apply.
	SI2	- ACI 117-10, Section 4.8.3, Class C-Surface. - Maximum gradual deviation over a distance of 5 ft (152 cm), or abrupt deviation is 1/2 in. (13 mm). - Limit deflection of formwork structure to $L/360$. - ACI 117-10, Section 4.8.2 does not apply.
	SI3	- ACI 117-10, Section 4.8.3, Class B-Surface. - Maximum gradual deviation over a distance of 5 ft (152 cm), or abrupt deviation is 1/4 in. (6 mm). - Limit deflection of formwork structure to $L/360$. - ACI 117-10, Section 4.8.2 does not apply.
	SI4	- ACI 117-10, Section 4.8.3, Class A-Surface. - Maximum gradual deviation over a distance of 5 ft. (152 cm), or abrupt deviation is 1/8 in. (3 mm). - Limit deflection of formwork structure to $L/400$. - ACI 117-10, Section 4.8.2 does apply.
Construction and facing joints[#]	CJ1	- Acceptable offset of surfaces between two adjacent placements ≤ 1 in. (25 mm).
	CJ2	- Acceptable offset of surfaces between two adjacent placements ≤ 1/2 in. (13 mm). - The use of chamfer strips or similar reveals are recommended at construction joints.
	CJ3	- Acceptable offset of surfaces between two adjacent placements ≤ 1/4 in. (6 mm). - The use of chamfer strips or similar reveals are recommended at construction joints. - Construction joint locations should be coordinated with architectural design.
	CJ4	- Acceptable offset of surfaces between two adjacent placements ≤ 1/8 in. (3 mm). Offsets less than 1/8 in. (3 mm) should be specified in design documents. - The use of chamfer strips or similar reveals are recommended at construction joints. - Construction joint locations should be coordinated with architectural design and approved by architect or engineer. - The mockup should contain all features representative to the finished product.

[*] Refer also to Chapters 5 and 7.

[†] Color uniformity is subjective and expectations for uniformity should be addressed before construction.

[‡] Concrete color deviations and discolorations cannot be completely eliminated, even using the best practices. If this is a concern, in addition to a mockup use a reference structure of similar size and finish.

[§] An approved mockup of the surface is required; even the best practices and quality control may result in minor color deviations and discolorations.

[‖] Surface irregularities do not apply for worked or textured areas.

[#] Construction joints that remain visible.

Table 3.1c—Form-facing categories

	Form-facing category		
Criterion	FC1	FC2	FC3
Holes, greater than 3/16 in. (5 mm)	Plug or disk covers are acceptable	Acceptable if patched sanded and sealed or ground to match adjacent form surface	Visible filling is unacceptable
Holes, 3/16 in. (5 mm) or less	Acceptable	Acceptable without patching, provided form surface is not damaged or torn around hole(s)	Acceptable if patched, sanded, and sealed or grounded to match adjacent form surface
Vibrator burns	Acceptable	Unacceptable	Unacceptable
Scratches/dents	Acceptable	Acceptable if patched, sanded, and sealed or grounded to match adjacent form surface	Unacceptable unless otherwise approved
Concrete remnants[*]	Acceptable	Unacceptable	Unacceptable
Cement residue[†]	Acceptable	Acceptable	Should not affect finished concrete surface
Swelling of facing at fastener or tie holes	Acceptable	Unacceptable	Unacceptable
Patching[‡]	Acceptable	Acceptable	Should not affect finished concrete surface

[*] Concrete remnant is hardened concrete on the form face.

[†] Cement residue is a thin film remaining on the form face.

[‡] Perform and inspect repairs of form facing and make acceptable for the intended formed concrete surface.

Table 3.1d—Concrete surface void ratio (SVR) on as-cast formed surfaces

Surface void ratio	SVR1	SVR2	SVR3	SVR4
Void area of pores of surface[*] occurring within a 24 in. x 24 in. square (610 x 610 mm)[*]	6.9 in.^{2} (4452 mm^2); D_{max} = 3/4 in. (19 mm)	5.8 in.^{2} (3742 mm^2); D_{max} = 5/8 in. (16 mm)	3.5 in.^{2} (2258 mm^2); D_{max} = 3/8 in. (9.5 mm)	1.7 in.^{2} (1095 mm^2); D_{max} = 1/4 in. (6 mm)
Suggested concrete placement practices to yield desired results	- Void area not to exceed 1.2 percent of the test area.	- Void area not to exceed 1 percent of the test area.	- Void area not to exceed 0.6 percent of the test area.	- Void area not to exceed 0.3 percent of the test area.
	- Standard formwork and placement practices should yield these results without any special effort. - This surface void ratio category limitation should not apply to permanently concealed concrete surfaces.	- Release agent should be compatible with the form-facing material. - Formwork should be cleaned before the application of release agent. - Apply release agent thinly and uniformly. - A mockup might be beneficial.	In addition to the efforts described for the SVR2 category: - Adequate vibration should be provided especially at features, openings, and embeds. - Concrete mixture consistency is important in achieving reproducible results. - Use revibration method at top lift. - Mockups are recommended.	- In addition to the efforts described for the SVR2 and SVR3 categories: - Concrete design and formwork should eliminate surfaces that inhibit the upward movement of entrapped air. - Placement rate should consider vertical ascent rate of entrapped air during consolidation. - Use methods of deposition that minimize agitation at the surface that introduces entrapped air. - Mockups are required.

[*] Void area is the summation of the areas of all voids within the sample space of 24 in. x 24 in. (610 x 610 mm). Voids with an average diameter of $d < 3/32$ in. (2.4 mm) are excluded from the calculation of the void area.

Note: If these criteria are made applicable to the project, then the mockup should demonstrate the ability of the contractor to meet the surface void ratio expected for these surfaces. The general appearance of the final structure should be compared with the general visual appearance of the mockup.

3.2 —Examples and determination of surface void ratio

Figures 3.2a(a),(b), and (c) through 3.2e provide views of concrete surfaces to aid in the understanding of the concrete surface void ratio determined in accordance with Tables 3.1a and 3.1d. These images are only provided as examples. Refer to 5.2.1, 5.2.2, and Chapter 7 for detailed descriptions for evaluating single criteria and the overall impression of a given concrete surface.

The surface void ratio is only required to be determined if the entire impression of the surface does not meet the contract expectation.

Wall views from distance Fig. 3.2a(a) and at measurement areas Fig. 3.2a(b) and Fig. 3.2a(c) with void area as single criterion.

The images in Fig. 3.2a(a), (b), and (c) through 3.2c only show examples of surfaces with void areas, also called "bugholes," that conform to SVR1 to SVR4 (Table 3.1d). They are not intended to show all aspects of CSC categories as noted in Table 3.1a.

1) Framed area with void count of 215 and maximum D = 1/4 in. (6.3 mm).

The method of measurement of void dimensions is shown in Fig. 3.2d. Using this method for the framed area in Fig. 3.2d, the total void area sums up to 2 in.^{2} (1300 mm^2).

Fig. 3.2a(a)—Large area viewed from a distance of 150 ft (46 m).

Fig. 3.2a(b)—Close-up view of wall Fig. 3.2a(a) with 24 x 24 in. (610 x 610 mm) measuring frame.

According to Table 3.1d, the determination would be surface void ratio category = SVR3. Measuring of surface voids is expected to be done manually as shown until opto-photographical methods become available.

2) Measurement of void length *l* and width *w* by interpolation to find approximate areas.

In arriving at the length and width, the objective for sizing the rectangle is to have about as much void area falling outside as non-void area falling within the rectangle.

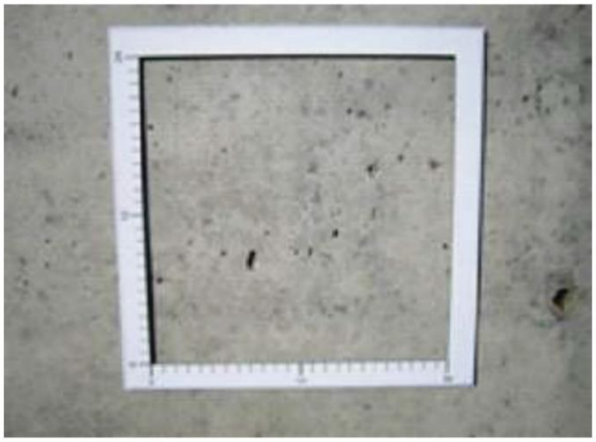
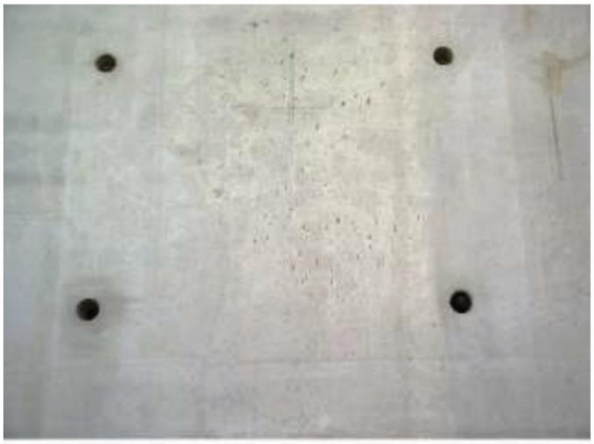


Fig. 3.2a(c)—Close-up view of wall Fig. 3.2a(a) at a different location.

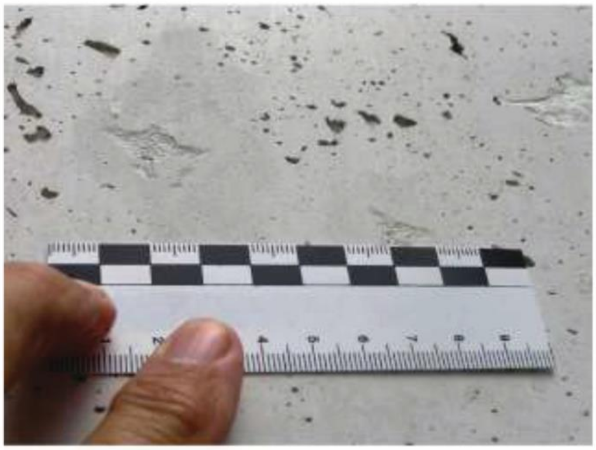


(a) Close view perpendicular to wall (tie holes as specified)

(b) Same wall surface, viewed at an angle

Fig. 3.2b—(a) Single area and (b) where summation of small surface voids viewed from distance indicate no sign of imperfection.

(a) General view of formed surface with high ratio of surface voids and imperfections



(b) Measurements of individual voids of (a)

Fig. 3.2c—(a) Single area with high ratio of surface voids; and (b) single size measurement of surface voids.

CHAPTER 4—BASICS OF LAYOUT AND DESIGN

4.1—General

After stripping formwork, the concrete surface will reflect the texture and other properties of the formwork. Based on the formed concrete surface category selected from Table 3.1a, the following features are considered for the formwork design:

a) Form-facing material;
b) Form face joint locations;
c) Form tie locations;
d) Reveals, such as size, shape, and patterns;
e) Properties of the concrete mixture design.

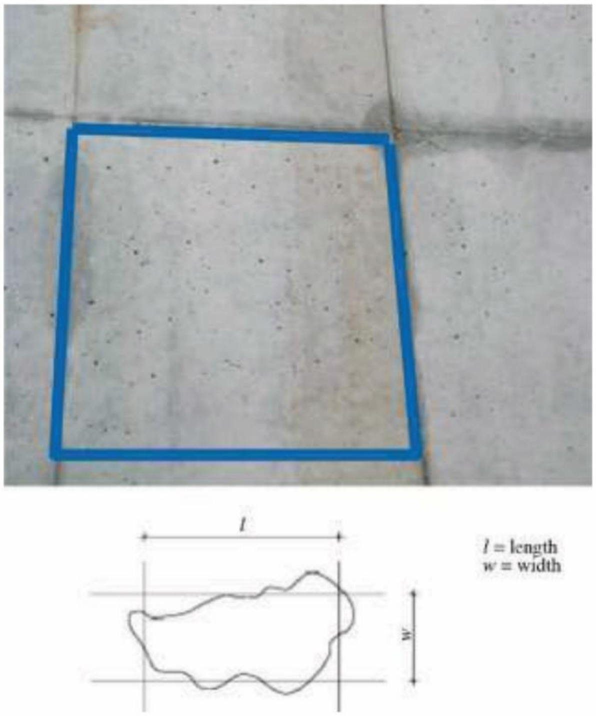


Fig. 3.2d—Example for measuring surface voids (refer to 1) and 2) as follows).

A formed surface appearance drawing describes the intended surface appearance of a specifically referenced, formed concrete surface. The use of formed surface appearance drawings help convey the desired features and appearance of formed concrete surfaces by showing all applicable features, such as: tie hole treatments; textured surfaces; reveals; fluting; fractured fins; sandblasted surfaces; geometric patterns; wood grain; exposed aggregates; reveals and rustications; construction joint appearances; integral color; form joint appearances, and modularity or other surface characteristics that affect the intended visual appearance of the finished work.

Figures 4.1a and 4.1b show the elevation of a finished wall and a plan view of a wall formwork layout done with panelized formwork. Figures 4.1c and 4.1d show the elevation of a finished wall and a plan view of a wall formwork layout done with job-built formwork. Both elevations show tie and form joint patterns. These elevations are sample figures and should be used for reference in 4.2 through 4.6.4.

4.2 —Design and construction recommendations

Requirements for the formed concrete surface can only be met if it is possible to place and consolidate the concrete properly. The following are design and construction recommendations (Refer to Table 3.1a):

a) Evenly arrange pouring windows and make sure they are of sufficient size to permit concrete placement. Pouring windows are openings in the formwork for placing concrete when placement from the top is not possible. Consider other compaction methods or mixture design modification— for example, SCC or high-flowable concrete—if pouring windows cannot be installed in the formwork without affecting areas exposed to view. Consider the locations and forming details of pouring windows in CSC2 and CSC3. Pouring windows are not recommended for CSC4. The use

APPENDIX B

Review of ACI 347.3R-13 “Guide to Formed Concrete Surfaces”

Page	Original Text	Comments
11	*The primary goal of the construction team is to produce as-cast concrete surfaces that meet project specifications and expectations Although various descriptions, interpretations, and methods exist to achieve an as-cast concrete surface, no unified definitions of different concrete surfaces exist.*	Sentence 1: Expectations can’t be a separate goal. Project specifications must be written such that contractors have a clearly defined path that will lead to expectations being met. Any expectations not addressed in the project specifications are unlikely to be met. Considering changing sentence to: “…that meet expectations prescribed in project specifications.” Also, the phrase as-cast doesn’t make it clear that his document does not apply to plant- or site-cast precast concrete.
12	*This document defines four quality levels of formed concrete surfaces and* provides methods to achieve and evaluate them. *These quality levels are identified by three surface finish categories: 1) form facing; 2) concrete surface void ratio; and 3) characteristics of form-facing materials. The basic procedures for classification are defined using tables derived from recommendations of the German Concrete Association (DBV) (Merkblatt Sichtbeton Deutscher Beton- und Bautechnik-Verein e.V. 2004).*	Sentence 1: The methods described in this document are too general for use in achieving the four quality levels. The described methods for evaluating the quality levels are sometimes objective and sometimes subjective. In some cases, the objective methods are subordinate to the subjective methods of evaluation. This leads to the following question: Why prescribe an objective method that requires financial resources for measurement if it can then be overridden by a subjective opinion? Sentence 2: The numbers or words don’t match the language in the document. Section 3.1 on page 2 states that “Four concrete surface categories (CSC’s) are defined in Table 3.1a.” Yet this sentence says there are three. Also, concrete surface void ratio is provided in Table 3.1d but Table 3.1c is called “Form facing categories”. Is “form facing categories” described by 1) form facing or by 3) characteristics of form-facing materials? Again, the numbers or words in this section do not match those in the document. Sentence 3: Need to check and compare differences between ACI 347.3R and the German document.
13	*This guide assists the project owner, design team, contractor, formwork and concrete suppliers, and all other parties in reaching a more specific understanding of how to produce a more clearly defined as-cast concrete surface. All other parties should understand the procedures, processes, and costs for producing defined surfaces of formed concrete. The guide also discusses all phases of construction relating to concrete surfaces from planning, description of work,*	Sentence 1: What does produce mean here? Construct? Specify? Or both? Sentence 2: What are the other parties? Shouldn’t they be named?

	and construction through acceptance of a concrete surface.	
14	*This guide can be used by both specifier (architect/licensed design professional) and contractor as a supplemental tool for defining, specifying, and evaluating concrete surfaces and offers guidance to the development of concrete surface specifications and expectations. Please refer to ACI 303R-12 for information regarding post-construction treatment of formed concrete surfaces*	Sentence 1: No other ACI documents uses the term "architect/licensed design professional." That makes it sound as if the architect is not a licensed design professional. Suggest using "licensed design professional." Sentence 1: If this Guide is a supplemental tool, it should cite other tools for defining, specifying, and evaluating concrete surfaces. And if it supplements other tools, what is the order of precedence for the different tools. Which is the ultimate controlling authority? Sentence 2: In reviewing ACI 303R-12 it is unclear what this statement is referring too; perhaps Chapter 10 Treated Architectural Surfaces? This needs to be better defined so the reader can understand what ACI Committee 347 wants the reader to find in ACI 303R-12.
2 Col.1 1	**CHAPTER 1—INTRODUCTION, p. 2** *The scope of this guide is to solve a lack of uniformity in the appearance criteria of concrete surfaces…*	Lack of uniformity implies that there are criteria but that they are not in agreement or are not uniform. That doesn't seem to be what is meant here. The document appears to be saying there is a lack of criteria, as is then illustrated by the discussion of the ACI and ASCC documents. The underlined portion is also clumsy sentence construction.
2 Col.1 1	*…provide definitions for the various levels of formed concrete surfaces, and give objective evaluations of them.*	All of the evaluations are not objective. For instance, the "overall impression" as stated in section 7.2 is certainly subjective.
2 Col. 18	*These references, which exclude uniform appearance criteria or a process for evaluating formed concrete surfaces, make it difficult to achieve a wide range of expectations.*	The word "exclude" makes it sound as if all of the references cited purposely left out appearance criteria or a process for evaluating formed concrete surfaces. ACI 301 does include a process. And again, the word "uniform" is not the correct word, nor is it needed.
2 Col. 19	*The ultimate authority on a project is the contract document. The contract document is a guide for the:*	The contract document is not a guide, which in ACI terminology is a document written in non-mandatory language. Document should be plural, because there are several contract documents for all projects.
2 Col. 1 b)	*Owner to understand what the final product approximately will look like*	For Owners to understand what the product will look like, they would need to know how the contract documents—especially the specifications—relate to their expectations. They may not have enough experience to do that. It's up to architects to understand the Owners' expectations, then write project specifications that are most likely to satisfy the Owner. Also, the phrase "approximately will look like" is both vague and clumsily written.
2 Col. 1 c)	*Contractor to select facing materials, concrete mixture, release agents, and construction methods to achieve the specified surface finish.*	Contractors don't often get to select facing materials, concrete mixtures, and release agents without restrictions. The specifications provide parameters on these selections. The other issue is that according to Table 3.1a, if the contractor chooses an

		“absorbent” or “nonabsorbent” form face material, that changes the surface void ratio and color uniformity requirements. That doesn’t seem appropriate.
	CHAPTER 2—DEFINITIONS	
2 Col.2	***area exposed to view***—*portion of structure that can be observed by the public during normal use.*	This sequence of these words “area exposed to view” is found nowhere else in the document. There is one mention of “areas exposed to view” in Section 4.2. But do we need a definition? The whole premise of the appearance requirements in this document applies to concrete surfaces exposed to view. If the surfaces aren’t exposed to view, why would we care about appearance?
2 Col.2	**flatness**—deviation of a surface from a plane.	Flatness is used only twice in this document – once in the definition and once in Section 3.1, General, as follows: “Tables 3.1a through 3.1d define the various measurable properties pertaining to formed concrete surface texture, surface void ratio, color, flatness, and joints.” Based on the general definition and industry usage of flatness, ACI 347.3R does not provide measurable properties with respect to flatness. Limits on abrupt irregularities don’t refer to flatness and are measured in a different manner than flatness. Suggest deleting this definition.
2 Col. 2	**gap**—space between abutting edges of the form-facing materials measured on the plane of the form surface.	Does “form surface” mean “formed surface?” Gaps between adjacent formwork components are described in Table 3.1b – Description of visible effects on as-cast formed surfaces. The statement in Table 3.1 b, for instance, T1 “Acceptable gaps in adjacent formwork components ≤ ¾ in” seems to be measured on the forms and NOT the formed surface. The definition of gap says it is measured on the form surface. This is at odds with the title of Table 3.1b. There is a difference between a form surface and a formed surface. There is another issue with the following statement in Table 3.1b: “Form-facing material example: Rough sawn lumber, CDX plywood and particle board.” It’s not clear how this relates to visible as-cast formed surface. It only describes materials that can be used to provide appropriate as-cast formed surfaces.
2 Col. 2	**mockup**—a sample of a component of the building as specified in the contract documents that is used to establish the expected surface finish.	This definition is inadequate. The specifications describe the surface finish and the mockup establishes whether the construction methods and other specified materials result in the specified finish. The “expected” surface finish can differ from the specified surface finish, and that introduces uncertainty and increased risk for the contractor.
2 Col.2	**reference area**—a significantly large area of a completed concrete surface serving as a basis of comparison for the acceptance of a surface category of work at a specified location of a given project.	A “significantly large area” is a vague, undefined term. Also, the definition states that the reference area serves as a basis for comparison for the acceptance of a surface category, but that doesn’t seem correct with respect to the document’s use of the words “surface categories.” Is there a reference area for surface categories CSC1 to CSC4? It seems some of the surface categories don’t need a reference area.

7	**CHAPTER 3—FORMED CONCRETE SURFACE DESCRIPTIONS**	
2 Col. 21	Tables 3.1a through 3.1d define the various measurable properties pertaining to formed concrete surface texture, surface void ratio, color, flatness, and joints.	Color is not a measurable property in this document. As stated in the footnote in Table 3.1b: “color is subjective…” The word flatness is not used in any of the Tables.
2 Col. 21	The surface void ratio is defined and categorized according to net pore area.	The phrase “net pore area” is used only once--at this location in the document. Recommend using a term that is included in Table 3.1d.
2 Col. 2 Last 3 lines	Concrete surface finish schedules should be designated as part of the contract documents in drawings or by designations on exterior/interior views of the structure.	An example of a concrete surface finish schedule would benefit the reader.
3 Table 3.1a	Top lines: CSC requirements[†][‡] Additional requirements	Note the word “requirements” as indicated: The word “requirements” is highlighted in this Table because ACI Technical Committee Manual (TCM) states that a Guide can’t provide requirements. The table provides recommendations and requirements, but “requirements” are not permitted in an ACI Guide. According to ACI 2104 TCM….7.2.1 Guides ACI guides present committee recommendations. ACI guides are written in nonmandatory language. Mandatory language can be used in nonmandatory-language documents when quoting directly from or referring to provisions in a document that uses mandatory language or is suggesting requirements.
“	Vertical column for CSC1, CSC2, CSC3, CSC4 Basic Requirements Normal Requirements Special Requirements	Note the word “requirements” as indicated and see comment above.
“	In Description for CSCI: Concrete surfaces in areas with low visibility or of limited importance with regard to formed concrete surface	Two vague phrases underlined here. Is the meaning the same as “not exposed to view?” This differs from “low visibility” (as in a fog?). Or “of limited importance” (as in the inside surface of as cooling tower?). Further, the description also says “…or covered with subsequent finishing materials.” The phrase “subsequent finishing materials” needs to be better defined. If the formed surface is to be covered with a waterproofing material, or is to be painted, this basic requirement, which might be viewed as the default, will not be acceptable. Bugholes as large as ¾ in. in diameter could be problematic for any spray-applied or roll-on coating.
“	CSC4 Mockup column. Should be required	See notes about mandatory language.
“	First footnote: [*]For matching requirements of formed concrete surface categories, please refer to the following notes and tables.	What does a matching requirements mean? Does it mean “meeting requirements?”

"	2nd footnote: †The appearance of the formed concrete surface should only be judged in its entirety not by looking at separate criteria only. The failure of one agreed criterion according to this guide should not result in the obligation to repair deviations if the overall positive image of the structure or the building is not disturbed.	The two underlined vague descriptions are extremely subjective. They seem to be saying, in the first case, that meeting separate criteria, such as those for surface void ratio, can be ignored if the surface is judged in its entirety to be acceptable. In the second case, they seem to be saying again that even if separate criteria, such as surface void ratio, are not met, no repairs are needed if the positive image of the building is not disturbed. So objective requirements can be overruled by subjective requirements. From the Introduction: The scope of this guide is to solve a lack of uniformity in the appearance criteria of concrete surfaces, provide definitions for the various levels of formed concrete surfaces, and give objective evaluations of them. But if subjective evaluations can always overrule objective evaluations, why would we waste time and money making measurements to satisfy objective criteria that can be overruled by a subjective opinion?
"	3rd footnote: ‡These requirements/features are described in detail in Table 3.1b.	Should replace "requirements" with "recommendations." This is an ACI Guide. See previous comments regarding mandatory language not being permitted in ACI Guides.
"	4th footnote: §Void area of pores of surface. Refer to Table 3.1d; legend: a = absorbent form facing; and na = nonabsorbent form facing.	The document does not provide a definition of "absorbent" and "nonabsorbent"; so how does the reader decide? Does using a form release agent change the definition of absorbent or nonabsorbent? Also, Table 4.6.4, Characteristics of various form-facing materials state the moisture resistance as "absorbant", "semi-absorbant" and "nonabsorbant". Yes, they are all spelled incorrectly in this Table. But where do semi-absorbent form-facings fit into the recommendations for surface void ratio and color uniformity in Table 3.1a since it lists only absorbent and nonabsorbent facings. Should Table 4.6.4 be referred to here so the reader knows what the definitions of these three terms are?
"	5th footnote: ‖The general impression of existing or not existing discolorations can usually be seen only after a longer period of time and for at least 8 weeks. The uniformity of coloring should be judged from the common viewing distance (Chapter 7).	The "general impression" is another subjective phrase. Can "not existing" discolorations ever be seen? And it's unclear how long the contractor has to wait if it's at least 8 weeks. Could it be 5 years? Also, the phrase "common viewing distance" is used only in the notes to this table and is not used in Chapter 7.
4	**Table 3.1b—Description of visible effects on as-cast formed surface**	There's a difference between "formed surfaces" and "form surfaces." This table should include only

Table 3.1b		visual effects that are visible on the as-cast surfaces: The recommendations for form-facing materials apply to “form surfaces” as does the gap in adjacent formwork. To control gaps in formwork, should fin width be indicated?
“	T1-T3 Acceptable depth of mortar loss: ½, 3/8, ¼ in.	How were the “acceptable depths of mortar loss” chosen? The stated values of ½, 3/8, and ¼ in. imply that contractors can control mortar loss to within 1/8 in. increments. Do these values refer to height of fins?
“	T1-T3 Imprints of modular panel frames are acceptable.	Why does this document consider only “imprints of modular panel frames?” Are imprints of plywood panels acceptable if they aren’t in a modular panel frame?
“	Criterion column for Classifications T1 through T4 refers to “Texture, Panel-Joint”	Texture refers to the visual and tactile appearance of a surface. A panel joint is generally a line and not a surface. So it sounds as if this might refer to the texture of the panel-joint face (perpendicular to the face of the sheathing), but it’s doubtful that this was the intent.
“	T1 Allowable projections 1 in. (25 mm) from adjacent surface. (ACI 301-10, Section 5.3.3.3.a).	Is this different or the same as that described in ACI 117-10, Section 4.8.3, Class D? ACI 117 states this is measured at the panel joint but citing ACI 301-10 seems to open the door to all surface projections so perhaps it doesn’t belong here in the panel-joint criterion? What was the intent of ACI Committee 347?
“	- T1 Form-facing material examples: Rough sawn lumber, CDX plywood, and particle board.	This is not a visible effect on a formed surface. Should be moved to another location. Same applies to form facing material recommendations for T2 through T4.
“	T4-Formwork should be grout tight. Avoid grout/mortar leakage and correct where occurs. - Permissible surface offsets of panel joints up to 1/8 in. (3 mm) (ACI 117-10, Section 4.8.3, Class A).	Not in same format as above on what is acceptable. Should this say that grout leakage is unacceptable? Why state that this has to be corrected? Shouldn’t all unacceptable items in this table be corrected? Why single out correction of this specific item? Now the word is “permissible” for surface offsets. In Table 3.1b, the words allowable, acceptable, and permissible have all been used. Are there nuances of meaning here? Or do they all mean the same thing?
“	- CU1. Light and dark color variations are acceptable. - CU2. Gradual light and dark discolorations are acceptable. - Color consistency between adjacent placements and layer lines should be mostly uniform	“Light and dark color variations” is a subjective phrase. “Gradual light and dark color discolorations” is a more subjective phrase. And what’s the difference between a color variation and a discoloration? The terms “color consistency” and “mostly uniform” are subjective. The footnote for CU1-CU3 says: “Color uniformity is subjective and expectations for uniformity should be addressed before construction.” That’s not very helpful because it’s unclear as to how expectations for uniformity should be addressed. With photos? The footnote for CU2 says: “Concrete color deviations and discolorations cannot be completely eliminated, even using the best practices. If this is a concern, in addition to a mockup use a reference structure of similar size and finish. The committee suggests using both a mockup and a reference structure. Which of these

		two is the controlling criteria for acceptance? Why use both if one will be the primary control? There are no measurables for color, in spite of the earlier statement in this section that: “Tables 3.1a through 3.1d define the various measurable properties pertaining to formed concrete surface texture, surface void ratio, color…”
“	- CU3 Discolorations caused by concrete source material of different type and origin; different types or treatments of facing materials; or inconsistent treatment of concrete surfaces are unacceptable - CU3 Rust stains, dirt stains and visible pouring layers are unacceptable.	If a discoloration is caused by something other than the causes listed—such as curing water--is it acceptable? Does a “visible pouring layer” differ from the “layer line” referred to under the CU2 classification?
“	SI1-SI4 footnote: Surface irregularities do not apply for worked or textured areas.	What are the definitions of “worked” or “textured” areas? Is a rubbed surface a “worked” area? And why don’t surface irregularities apply?
“	- SI1 ACI 117-10, Section 4.8.3, Class D-Surface. SI2 SI3 -SI1 Maximum gradual deviation over a distance of 5 ft (152 cm), or abrupt deviation is 1 in. (25 mm). SI2 SI3 - SI1 Limit deflection of formwork structure to *L*/240. SI2 SI3 SI1 ACI 117-10, Section 4.8.2 does not apply. SI2 & SI3	Different format than used in T1-T4—why? I don’t think it is clear to the reader that the second item listed is a paraphrasing of ACI 117-10 requirements for Class D. This is not stated correctly in accordance with ACI 117 because the gradual deviation is measured with a 5 ft. straightedge resting on high spots but the deviation is measured between the high spots. The distance between the high spots could be 5 ft. or less. How is this related to a visible effect on an as-cast surface? The L/240 recommendation in ACI 347 and a similar requirement in ACI 301 is for “facing materials,” not the “formwork structure.” Formwork for Concrete (SP4) illustrates how to calculate the deflection of plywood supported by studs, studs supported by wales, but does not show how to calculate the deflection limit for a “formwork structure.” As stated, the phrases “Limit deflection …to L/240, L/360, or L/400 are meaningless because no clear span is given. For instance, ACI 301-16 states such limits as follows: **6.2.2.1.a** Design forms that produce required finish. Limit deflection of facing materials between studs and deflection of studs and walers to 0.0025 times the clear span (*L*/400). What is the intent of this? Why tell the reader in this section that plumb doesn’t apply? Why doesn’t plumb apply?
“	SI4	Same comments as for SI1. But why does plumb apply?
“	Criterion column for CJ1 through CJ4	What is the difference between a “panel-joint,” as stated in Classification T, and a “facing joint” as used here? Are they the same?
“	CJ2, CJ3, and CJ4 The use of chamfer strips or similar reveals is recommended at construction joints.	This differs from other entries in this table because it doesn’t provide an acceptance criteria for the as-cast surface. It is simply a suggestion for construction.

“	CJ3 Construction joint locations should be coordinated with architectural design.	This does not provide an acceptance criteria for a visible effect of an as-cast formed surface
“	CJ4 Acceptable offset of surfaces between two adjacent placements 1/8 in. (3 mm). Offsets less than 1/8 in. (3 mm) should be specified in design documents. CJ4 Construction joint locations should be coordinated with architectural design and approved by architect or engineer. The mockup should contain all features representative to the finished product.	Why design document? What about contract documents? Why tell the reader at this point in the document that offsets less than 1/8 in. should be specified? All offsets, not just those less than 1/8 in. should be specified. Why in CJ3 should it be coordinated with architectural design but in CJ4 it must also be approved by architect or engineer? This does not provide acceptance criteria for visible effects on an as-cast surface as is indicated in the title of Table 3.1b.
5 Table 3.1c	Column FC3 [Holes] Acceptable if patched, sanded, and sealed or grounded to match adjacent form surface Assume grounded is a typo—should be ground?	What if this patching, sanding, sealing, or grinding leaves a visible effect on the as-cast formed surface? Is that acceptable?
“	Criterion column lists “Vibrator burns”	This term is used only in ACI 347.3R-13 and in no other document in the MCP. Nor is it listed in ACI CT-13. Thus it should be defined.
“	Column FC3 [Dents and scratches] Unacceptable unless otherwise approved	Who approves dents and scratches in form facing? Do architects or engineers ever inspect form facing?
“	Footnote: Perform and inspect repairs of form facing and make acceptable for the intended formed concrete surface.	Should this state “for the intended form-facing categories” instead of formed concrete surface?
5 Table 3.1d	General comment on Surface void ratio	This table implies that contractors know how to, or can be told how to, use construction methods that are sophisticated enough to consistently produce SVRs within the stated ranges of 1.2%, 1%, 0.6% and 0.3%. Is this realistic? The “suggested concrete placement practices to yield desired results” are so vague that it is difficult to see how this is possible. There is also a significant digits problem for SVR2. By listing the maximum percent as 1% instead of 1.0% implies that a value of 1.4% would be acceptable, based on rules for rounding of measured values. See ASTM E29-13, “Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.” The German document uses a maximum value of 0.9% for SVR2, which is correct.
“	General comment	The table also implies that contractors know how to or can be told how to control bughole size in 1/16- or 1/8-inch diameter increments.
“	Surface Void Ratio (SVR) is the pore void area is a percentage of the area of a 2x2-ft sample.	How many samples are needed and how are the samples locations chosen? This is a critical issue that is not discussed.

“	- SVR2 column: Release agent should be compatible with the form- facing material. - Apply release agent thinly and uniformly	What does compatible mean and how is it evaluated? What does “thinly” mean and how is it evaluated? How is “uniformly” determined?
“	- SVR3 column: Adequate vibration should be provided especially at features, openings, and embeds. Concrete mixture consistency	Adequate vibration is a vague phrase. Can something more helpful be added? Perhaps a reference to ACI 309 publications? I assume consistency in this sense refers not to a specific slump, but to variations in slump or other plastic properties. Which properties need to be consistent and what range for these properties is considered consistent?
“	- SVR4 column: Placement rate should consider vertical ascent rate of entrapped air during consolidation. - Use methods of deposition that minimize agitation at the surface that introduces entrapped air.	What is “vertical ascent rate of entrapped air?” Does it refer to how rapidly air bubbles stop appearing on the unformed surface of the concrete? How does one determine this? Is it related to lift thickness? And what should the contractor do to consider it? What does this mean? Please describe methods that the committee believes will minimize agitation.
“	Footnote: Void area is the summation of the areas of all voids within the sample space of 24 in. x 24 in. (610 x 610 mm). Voids with an average diameter of $d < 3/32$ in. (2.4 mm) are excluded from the calculation of the void area.	How is the average diameter calculated?
“	Footnote: If these criteria are made applicable to the project, then the mockup should demonstrate the ability of the contractor to meet the surface void ratio expected for these surfaces. The general appearance of the final structure should be compared with the general visual appearance of the mockup.	Elsewhere, this document states if the “overall impression” is suitable, the surface void ratio doesn’t need to be calculated. This footnote seems to contradict that view. Also, the term “overall impression” is used often in this document. Is that the same as “general appearance?” Recommend consistency in terms.
5 Sect. 3.2	The surface void ratio is only required to be determined if the entire impression of the surface does not meet the contract expectation	The last sentence in the preceding paragraph used the phrase “overall impression” which differs from the “entire impression.” Should use same phrase throughout the document for consistency. We have contract documents and owners expectations, but how does a contract have an expectation?
“	The images in Fig. 3.2a(a), (b), and (c) through 3.2c only show examples of surfaces with void areas, also called “bugholes,” that conform to SVR1 to SVR4 (Table 3.1d).	The figures do not indicate the surface void areas. Which figures conform to SVR1 to SVR4?
“	The method of measurement of void dimensions is shown in Fig. 3.2d. Using this method for the framed area in Fig. 3.2d, the total void area sums up to 2 in.^{2} (1300 mm^2).	The method of measurement is shown in Fig. 3.2d but it’s unclear as to the framed area the 2 in^2 refers to. Is it the photo above the drawing, or is it the framed area shown in Fig. 3.2 a(b) or 3.2a(c)? The figure numbering system is confusing.

6 Sect. 3.2	*Fig. 3.2a (a)—Large area viewed from a distance of 150 ft (46 m).*	*Why a 150 ft. distance? Chapter 7 says 20 ft. or more; is this figure implying that 150 ft. is the appropriate viewing distance?*
“	Measurement of void length *l* and width *w* by interpolation to find approximate areas.	How are l and w measured by interpolation? That doesn’t make sense and isn’t consistent with Figure 3.2d.
“	In arriving at the length and width, the objective for sizing the rectangle is to have about as much void area falling outside as non-void area falling within the rectangle.	In essence, this is not a measurement. It’s an estimate.
“	*Fig. 3.2b(a) and (b).*	*What is the point of these two photos? That viewed at an angle, the bugholes are less noticeable? But they’re being measured from the view perpendicular to the wall.*
7 Sect. 3.2	*Fig. 3.2c—(a) Single area with high ratio of surface voids; and (b) single size measurement of surface voids.*	*It would be helpful to know the measured surface void ratio for the wall in the photo so the reader could get a mind’s-eye impression of, say, a SVR of 1.4%, or whatever the high SVR was.*
	CHAPTER 4—BASICS OF LAYOUT AND DESIGN	
7 Chapt 4	4.1 After stripping formwork, the concrete surface will reflect the texture and other properties of the formwork.	Texture seems to be used to describe both the panel-joints and the overall surface; however while there are texture recommendations for panel joints, there are none for the overall surface.
7 4.1	b) Form face joint locations; c) Form tie locations;	Table 3.1b shows only construction joint locations to be coordinated with architectural design – not form face joints. Unclear why this is stated here. Based on Table 3.1a, are there any recommendations for form tie locations? Should there be?
7 4.1	A formed surface appearance drawing describes the intended surface appearance of a specifically referenced, formed concrete surface.	This phrase appears four times in the document, but an illustration would be helpful. Are Figs.4.1a or 4.1c examples of such a drawing?
7 4.1	The use of formed surface appearance drawings help convey the desired features and appearance of formed concrete surfaces by showing all applicable features, such as: tie hole treatments; textured surfaces; reveals; fluting; fractured fins; sandblasted surfaces; geometric patterns; wood grain; exposed aggregates; reveals	What is a textured surface, as mentioned here? Fractured fin sandblasted, and exposed-aggregate are textured surfaces. “reveals” are mentioned twice.
7 4.1	Both elevations show tie and form joint patterns.	CSC tie or joint pattern requirements aren’t listed in Table 3.1a. Should they be?
7 4.2	The following are design and construction recommendations (Refer to Table 3.1a).	Why is Table 3.1a referenced here? It doesn’t seem relevant to the following discussion.
7-8 4.2	The use of filling nozzles may be required for placing highly flow able concrete or SCC.	What is a filling nozzle?
8 4.2	b) Verify that spacers will not affect the appearance of the finished surface by corroding, protruding, or being recognizable at the surface of the formed concrete surface, especially in CSC3 and CSC4.	How does the contractor verify this? With a mockup?

8 4.2	e) At recesses, reveals, flutes, rebates or other locations …	What is a rebate?
8 4.3	This formed surface appearance drawing helps to match expectations with the final appearance of the formed concrete surface.	Need to match specifications with the final appearance of the formed concrete surface. The specification tells the contractor how to produce the desired appearance.
9 4.3	Below Fig. 4.1b In planning and detailing formwork for acute-angled walls, sharp corners, edges, and other abrupt or unusual shapes, it is possible for edges to be damaged.	Sentence doesn't make sense. Edges can't be damaged during the planning and detailing.
9 4.3	When designing the formwork, anticipate conditions that can result in air becoming trapped during placement and make provisions for venting the air or for modifications to the concrete placement method to avoid surface voids or bug holes.	We can't avoid surface voids, and this document allows some surface voids. Use the word "minimize" instead of "avoid."
9 4.4	Form panels may create differences in the concrete surface appearance when reused over the course of the project (Table 4.6.4).	What can the contractor do to minimize differences in appearance? Reuses should be limited to some number? Inspector follows progress and notes when differences start to appear so those reused forms are no longer in service?
10 4.4	Below Fig. 4.1d Nonabsorbent facings produce lighter concrete surfaces, and color differences, such as mottling, become more apparent.	What's the effect of semi-absorbent form-facing, which is also mentioned in this document?
10 4.4.2	…dimensional changes with use may impact form concrete surface…	Replace "form" with "formed."
10 4.4.2	g) Attention should be given to selection and application of release agents based on form facing-type;	"Attention" is a vague word. What kind of attention?
10 4.5.2	Depending on the quality of the facing material and on how the formwork is assembled, only form-facing seams could be visible at most.	What is the meaning of "visible at most?"
11 4.5.4	c) The age of plywood facings influence the color uniformity because of different usage numbers. Panels not in compliance should be repaired or removed;	The age…influences the color uniformity. Panels not in compliance with "what" should be repaired or removed? If this sentence refers to color variation in the formed surface, it's discovered only after the plywood facings have already been reused too often.
11 4.6.1	Depending on the quality of facing material and on formwork assembly, only form-facing seams could be visible at most	Again, what is the meaning of "visible at most?"
11 4.6.3	Follow the manufacturer's technical data for maintenance and installation requirements.	What manufacturer's technical data should contractors follow if they're using job built forms? Manufacturer of the plywood?
12 Table 4.6.4	Far left: Moisture resistance is misspelled. Absorbent is misspelled.	Proof reading was poor for this document.

	CHAPTER 5—SPECIFICATIONS	
14 5.2	Specifications should… describe the desired look of the formed concrete surface, which include surface features such as: a) The CSC according to Table 3.1a;	Specifying a specific Concrete Surface Category (CSC) isn't enough. The content of the recommendations for the CSC must be stated in the required mandatory specification language. But before that is done, we need to determine whether or not this can be done with achievable and measurable requirements.
14 5.2.1	Incorporate into the mockup building geometries the: reinforcing bar cover, reinforcing bar finish …	What is "reinforcing bar finish?" Does this refer to black steel, epoxy-coated, stainless steel, or galvanized bars?
14 5.2.1	The contractor should confirm in writing that the mockup quality represents work that can be accomplished in the actual structure.	What if it can't be accomplished in the actual structure?
15 5.3	f) Alkali streaks	What is an alkali streak? Does this refer to efflorescence?
	CHAPTER 6—CONSTRUCTION	
15 6.1	i) When locating concrete placement windows or other temporary openings in formwork	All other references to these openings in this document call them "pouring windows." Consistency is needed. Neither pouring windows nor placement windows are listed in ACI CT-13, so there is no formal definition. ACI 309R-05 calls them "placing ports."
15 6.2	d) With extended duration between reinforcement delivery or installation and concrete placement, there is a risk of stains on the concrete surface due to mill scale, rust, or both— particles on the concrete surface that cannot be removed. Staining may be more pronounced on horizontal surfaces. If rust stains on the underside of horizontal surfaces need to be avoided, use noncorrosive reinforcement as determined in the specifications;	Is this suggesting that reinforcing bars in the bottom of beams and slabs must be free of rust and mill scale? That is not a very practical suggestion. Also, the correct word is "noncorrodible" not "noncorrosive."
16 6.2	i) When locating concrete placement windows or other temporary openings in formwork, avoid areas of congested reinforcement. Consider the concrete's finished appearance when selecting the location of temporary openings because such openings will most likely leave a form imprint on the finished surface.	These openings in the forms are needed most in or near areas of congested reinforcement. That's where the vibrator operator and inspector have to verify that the concrete has been adequately consolidated. Such openings are certain to leave a form imprint. And if both sides of a wall are exposed, form openings are not an option unless a further acceptable treatment of the as-cast surface is planned.
16 6.3	c) Mixture designs that produce high alkaline concrete will wear out form-facing materials faster, especially for overlaid plywood. This could result in fewer reuses. Low *w/ cm*, Class C fly ash, and mixture characteristics can create concrete with high alkalinity.	All fresh concrete has a high pH. A reference is needed to provide data regarding effect of alkalinity on reuses of overlaid plywood and the effect of the factors in the underlined sentence.
17 6.2	The appropriate viewing distance is equal to the distance that allows the entire building, the building's essential parts, or both, to be viewed in their entirety. The individual design features should be recognizable.	If bugholes are to be considered as individual design features, they will rarely be recognizable at a viewing distance that allows either the entire building or its essential parts to be viewed in their entirety. Thus, the Surface Void Ratio would be irrelevant in most cases.
17 6.4	a) Place concrete to the full height or in equal lifts and consolidated as required to avoid segregation;	Replace "consolidated" with "consolidate" and "removed" with "remove."

	b) Minimize mortar leakage. If there is leakage on the completed concrete surface, removed with fresh water as quickly as possible;	
	CHAPTER 7—EVALUATION OF FORMED CONCRETE SURFACES	
17 7.2	This viewing distance allows one to evaluate of the overall appearance of the structure has been achieved.	Replace “of” with “if.”
17-18 7.3.1	The failing of a single criterion will only obligate the repair of the defect. The entire surface impression depends on the size of the viewed area, which was agreed upon at the beginning of the project. For example, should the surface void ratio in some areas be higher in the finished work than specified, this alone is not sufficient reason for rejection of the entire work if the overall appearance is still achieved.	Again, the Surface Void Ratio would be irrelevant in most cases, for acceptance. But if repair is needed because the SVR recommendations aren’t met, does the contractor fill only enough surface voids (the largest ones) to meet the recommended level, or must the entire surface be rubbed?

Appendix C

Annotated Bibliography on Bugholes

Anon., “Avoiding Surface Imperfections in Concrete”, Data Sheet, Cement, Concrete & Aggregates Australia, July 2008.

> Lists practices for minimizing blow holes. 1. Use rigid, well-braced formwork. 2. Avoid battered forms. 3. Thin coat of non-sticky form release. 4. Use permeable formwork where appropriate. 5. Avoid “sticky” mixes—over-sanded, high air content, too lean. 6. Place concrete with maximum vertical rise of 2 m/hr. 7. Consolidate with vibrator of proper size and spacing of insertion points, and use proper technique. 8. Withdraw vibrator slowly to allow time for entrapped air to rise. 8. Make sure concrete near form is properly compacted. 9. Revibrate the top placement layer at about the same time as if a further layer was being placed on top.

Anon. (a), “Cresset Concrete Standards (CCS)”, Cresset Chemical Company, 1990

> A six-point classification from CCS 1 (smallest and fewest bugholes) to CCS-6 (largest and most bugholes), with actual size unretouched photos that illustrate the six classes. Recommends differing proprietary form release agents from the same company and film thicknesses for each class. Increasing film thickness results in more and larger bugholes.

Anon. (b), “How to Eliminate Bugholes,” Cresset Chemical Company, 1990

> Emphasizes using low-viscosity release agents in thinner layers to reduce bugholes. States there is no one, exact application technique for spraying forms because of differing tank pressures, tip orifices, and form type and surface characteristics.

Anon. “Flowing or Self-Consolidating Concrete,” Concrete Q&A, *Concrete International,* Feb. 2008, p.64

> Discusses the differences between flowing and self-consolidating concrete (SCC). Flowing concrete may require vibration for consolidation, whereas, SCC is not meant to be vibrated.

Anon. *A Guide to Specifying Visual Concrete,* http://www.irishconcrete.ie/downloads/Specifying_Visual_Concrete.pdf

> States the following under the subtitle, Surface Tolerances, b) Formed surface imperfections: “blowholes are permissible up to a max. size of (3 mm); their number may not exceed (10) in any square metre.” The values in parentheses appear to be default values. Also see Anon 2015.

Anon., “How to Prevent Troubles with Architectural Concrete Finishes, *Concrete Construction*, 1979.

> Preventive measures for bugholes include reducing the sand content or changing the sand gradation or type of sand. Use thorough internal vibration followed by low frequency external form vibration. Abrasive blasting exposes voids covered by a fragile cement-paste cover.

Anon., “Preventing bugholes (Problem Clinic)” *Aberdeen's Concrete Construction*, v. 40, no. 2, Feb. 1995, p. 215.

> Sticky or tacky concrete due to excessive sand is hard to consolidate and will have more bugholes. To minimize the effect, insert internal vibrator as close to form as possible, use proper vibrator spacing and duration of vibration. Avoid using vibrators with too large an amplitude and high-viscosity form release agents in thick layers.

Anon., *The Contractor’s Guide to Quality Concrete Construction, 3rd ed,*” American Society of Concrete Contractors and American Concrete Institute, 2005, p. 140.

Briefly describes bugholes and their causes. States they are more likely to occur in air-entrained concrete, but are caused by entrapped air. The entrained air makes it more difficult to work entrapped air or water to the surface. Reducing air and sand content reduces stickiness of the concrete. Many air-entrained mixes contain more sand than needed. Suggests reducing lift thickness and moving the vibrator as close as possible to the form surface, and inserting the vibrator more frequently [closer spacing].

Anon., *Visual Concrete,* mpa The Concrete Centre, 2015, p.9.

This publication provides guidance on formed concrete finishes. The subsection titled “Further formwork details,” recommends that the highest quality visual concrete should have no more than ten 3-mm diameter blow holes per square meter. See also: Anon. *A Guide to Specifying Visual Concrete*

Architectural Precast Concrete 3rd ed., Precast/Prestressed Concrete Institute, 2007, pp. 139, 153, 169, 240.

If surface air holes are of a reasonable size—1/8 to 1/4 in. –it is recommended that they be accepted as part of the texture. Filling and sack rubbing is expensive and may cause color differences. Surface air voids are accentuated when the surface is lightly finished or abrasive blasted. *“Contract documents must identify who the accepting authority will be: owner, general contractor, or site inspector. One person must have final and undisputed authority in matters of acceptability of color, finish, and texture, in compliance with the contract documents.”* Samples of the mockup panel should be used to establish acceptable air void size, frequency, and distribution.

Berger, Dean M., “Preparing concrete surfaces for painting,” *Concrete Construction*, v. 22, no. 9, Sept. 1977, p. 481-484.

If a coating bridges a bughole, the film dries from both sides and either blisters or shrinks, leaving a hole in the film.

Bissonnette, Benoit, Courard, Luc, and Garbacz, Andrzej, *Concrete Surface Engineering*, CRC Press, Boca Raton, FL, 2016, pp. 90-93.

Cites CIB 24 but states: “…it is difficult to evaluate blowholes over an entire surface by comparing with a small-size comparator.” A seven-level scale is placed on the concrete surface and an inspector views it from 3 to 10 meters depending on the standard used. To identify the blowhole level, the observer compares the scale with compares the scale with the concrete surface. “*This method is subjective and does not yield important information like the percentage of surface exhibiting voids [neither does ACI 347.3R-13], the estimated number of holes, and the hole size range.”*

“Bugholes in Formed Concrete*”, ASCC Position Statement #8*, *Concrete Internationa*l, August 2011.pp. 1.

Bugholes larger than sizes outlined in ACI 301-10 (Now ACI 301-16) are not defects. Because bugholes are a natural feature of all as-cast vertical concrete structural components, it is unrealistic to expect that surfaces, will be free of bugholes.

CIB Report No. 24, *Tolerances on Blemishes of Concrete*, Report prepared by CIB Working Commission w 29 “Concrete Surface Finishings,” 1973.

Classification method for off-the-form concrete surfaces based on two seven-photo sets showing varying size and frequency of blow holes and color differences (Class 7 has the highest and Class 1 the lowest incidence of blow holes). Divides surface into four classes: Rough (no requirements); Ordinary (appearance is a minor factor but still of some importance); Elaborate (Definite requirements for visual appearance); Special (calling for the highest standards of appearance). Divides blow holes into two groups: 1. Voids grouped in small areas and 2. Voids distributed over the entire formed surface. *Puts emphasis on not considering absolute values but variations over the whole surface. Thus,* *even for a Special class, a surface is acceptable even if it matches Class 6 photos provided that the blowholes are uniformly distributed.* The document also states that numerical values should be treated like strength test results, allowing some variance from “perfect,” e.g 95% for Special class, 80% for Elaborate class, and 70% for Ordinary class.

Coutinho, Joana Sousa, “Effect of controlled permeability form-work (CPF) on white concrete,” *ACI Materials Journal*, v. 98, no. 2, 2001, pp. 149, 151.

Laboratory study with white-cement, 3-in.-slump concrete. Two specimens, 600 mm x 900 mm face, 200 mm. thick cast in three layers and consolidated with immersion vibrators. “Special stripping wax for white concrete” used as form release. One face of one specimen CPF, other face impermeable plywood. One face of second specimen high-density five-layer wood-based formwork, other face impermeable plywood. Blow hole ratio (same as SVR) determined for each of the four faces by tracing blow holes on transparent paper and transferring this data to computer. Area of each blowhole was then measured and blow-hole ratio calculated. See Table 3 and Figs. 4 and 5. CPF face SVR = 0%. Opposite face SVR = 3.0%. High-density formwork face SVR = 5.2%. Opposite face SVR = 1.0%. Note 5.2%, 3.0% and 1.0% SVRs.

DBV Merkblatt Sichtbeton Deutscher Beton- und Bautechnik-Verein e.V, 2004.

This is the document on which ACI 347.3R-13 was based. We could not obtain a copy, but see Hillemeier, et al, in this bibliography for a summary of the requirements regarding surface porosity (SVR), and an assessment of these requirements. See also, Vikan (2007).

DBV Merkblatt Sichtbeton Deutscher Beton- und Bautechnik-Verein e.V, 2004, 2nd ed. Aug. 2008.

This is the 2nd ed. of the document on which ACI 347.3R-13 was based. The requirements for SVR are nearly the same as those in the ACI Guide except that the approximate maximum limits for the four SVR categories are 0.3%, 0.6%, 0.9% and 1.2%. The SVR is measured on a 500x500 mm test surface.

DBV Merkblatt Sichbeton Deutscher Beton- und Bautechnik-Verein e.V, June 2015.

This is the most current revision of the older document on which ACI 347.3R-13 was based. The requirements for SVR are the same as those in the 2nd ed. except that the SVR is measured on a 500x500 mm representative test surface. There are no guidelines for choosing the test surface or for measuring the area of bugholes. In Section 5.1.2, this document states in part:

> “The following characteristics represent properties or requirements that, independent of the agreed exposed concrete class, are technically not achievable or unerringly achievable, and which therefore, depending on the type of performance, cannot be expected unconditionally…:
>
> - An even color tone for the exposed concrete surfaces in the building;
> - Surfaces free of dark discolorations, at low temperatures and at high relative air humidity
> - Pore-free exposed concrete surfaces;
> - Uniform pore structure (pore size and distribution) in an independent surface, as well as in whole exposed concrete surfaces in the building;

It further states that pore accumulations in the upper parts of vertical construction components can be avoided only to a certain extent.

Section 6.3 lists the following measures, among others, that have proven useful for producing acceptable off-the-form concrete surfaces in everyday practice:

- A "robust" concrete type that doesn't cause substantial changes in surface appearance due to minor fluctuations in raw materials or homogeneity of the concrete;
- Concrete with a sufficient powder content to reduce sedimentation and bleeding as much as possible.
- A uniform ratio of water to cement, if possible not above w/c = 0.55
- No use of residual water, and reduction in delays of concrete delivery;
- Largest maximum size aggregate up to 16 mm, if possible smaller;
- Concrete pouring consistency F3 (soft) and higher [F3 concrete has a spread between 420 to 480 mm when tested per DIN EN 12350-5.]

Ford, J.H., “Troubleshooting common defects in vertical cast-in-place concrete,” *Concrete Construction*, v. 37, no. 12, Dec. 1992, p. 879-880.

To reduce the occurrence of bugholes, avoid concrete mixes with:

- High air contents
- Sands with a low fineness modulus
- High sand contents
- High paste contents

Chemistry, application rate, and viscosity of release agent can affect the development of bugholes. Permeable form liners decrease bugholes but may be too expensive.

Formwork for Concrete, Part 1: Documentation and surface finish (AS 3610.1—2010), Australian Standard®, Standards Australia, Sydney, Australia, 2010, 53 pp.

Gives physical qualities of five classes of surface finish. Table 3.2.1 includes applicability of the most demanding surface classes (1 through 3) for which visual quality is important. These are described as follows: Class 1 is subject to close scrutiny, Class 2 requires uniform quality and texture over large areas, and Class 3 requires good visual quality when viewed as a whole. For classes 4 and 5, visual quality is considered not to be important. A note indicates:

- Class 1 is recommended only for use in very special features of buildings of a monumental nature.
- Class1 shall not be specified for whole elevations or extended surface areas.

Table 3.3.2 refers to three photo sets of surfaces exhibiting differing blowhole sizes and distribution (Appendix A in *AS 3610.1--2010*). These are used as indicators of the requirements for the permissible size and frequency of blowholes for Classes 1-3. For each class there is a general photograph at scale 1:5 that gives a clear idea of expected variation in blowhole size and frequency. A close-up photograph at scale 1:1 shows an area that is representative of the general photograph.

Blowhole size and frequency are evaluated by comparison of the completed work with the relevant photographs for the Classes 1-3. The 1:1 scale photograph is held against the surface and viewed from a distance not less than the greater of 6 m or the closest distance from which the subject area will normally be observed when the project is completed.

A note indicates that printed photographs in Appendix A should not be photocopied or printed from a downloaded copy of AS 3610.1—2010 because they will not produce results consistent with those from an original printed photograph and should not be used for evaluation purposes.

Gaimster, Rob, “Self-Compacting Concrete, *Concrete*, April 2000, pp. 23-25.

SCC used in 12 heavily reinforced concrete columns, some 6 m and others 10 m in height. Target for slump flow was 700 mm. Minor blemishes observed were in the 6-ft-high columns and were attributed to the impermeable formwork and tapered design of these columns.

Guide to Identification and Control of Visible Effects of Consolidation on Formed Concrete Surfaces (ACI 309.2R-15) American Concrete Institute, 2015, pp. 7-10.

When concrete is stiff, placing rate must be reduced to allow adequate vibration and reduce bugholes. Bugholes can result when concrete is sticky due to high sand content, high entrapped air content, or both. High-amplitude vibrators or incomplete insertion of the vibrator head could result in an increased quantity of bugholes. To minimize bugholes:

- Space vibrator insertions at 1.5 times the radius of influence and remove the vibrator slowly.
- Consolidate each concrete layer from the bottom up.
- Increase vibration duration when using impermeable forms that permit air trapped at the form surface to escape through joints.
- Avoid battered forms and complex design details.
- Limit depth of placement layers.
- Be sure vibrator penetrates the previous layer.
- When practical, use a 2-1/2-in. diameter vibrator of high frequency and medium to low amplitude.
- Revibrate at the latest possible time at which the vibrator head will penetrate the concrete under its own weight. This is helpful with higher-slump mixtures, especially in the upper portion of the placement.
- Other measures such as altering mix proportions, using high-range water reducers, and using a smaller nominal maximum size aggregate to improve workability should be considered.

Guide to Cast-in-Place Architectural Concrete Practice (ACI 303R-12), American Concrete Institute, 2012, 32 pp. [Plus one excerpt from ACI 303R-04]

ACI 303R-04 Section 4.9.6

Generally speaking, the thinner the film of release agent applied to the form, the fewer bugholes and stains on the hardened concrete. The performance of some release agents, however, is not affected by film thickness. Testing before use is recommended.

ACI 303R-12 Section 5.9.6

In general, the thinner the film of release agent applied to the form, the fewer surface air voids and stains on the hardened concrete. The performance of some release agents, however, is not affected by film thickness. Testing before use is recommended. [Note: There is no citation for the source (or data) for either of the statements that performance of some release agents, however, is not affected by film thickness.]

ACI 303R-12

Further research is needed to provide additional information on surface air voids and other construction problems. Vertical construction joints with rustication strips can be detailed as crack-control joints. This permits the acceleration of the vertical rate of casting that, particularly in hot weather, will eliminate or make manageable the problems associated with surface air voids, form spatter, cold joints, and lift lines. When choosing release agents consider the permissible number and size of surface air voids on the concrete surface. Barrier-type release agents are not recommended because their use tends to produce more stains and surface air voids. There is a tendency for a lighter color and an increase in surface air voids in the concrete near the top of placement lifts due to decreased form pressures, inadequate vibration, and an increase in the *w/cm* at these locations. With proper proportioning, depending on the width of the forms and the amount of reinforcement, lifts can be up to 36 in. deep. Deeper lifts, accompanied by additional careful vibration, can be used with high-density forming to eliminate excess surface air voids. The surface of each layer should be sufficiently level so that the vibrator does not move the concrete laterally, as this might cause segregation. [Note: Other documents suggest that moving concrete laterally, especially SCC, decreases the incidence of bugholes.]

Hillemeier, Bernd; Herr, Roland; Kannenberg; Matthias; and Schubert, Karsten, "Exposed concrete—Formwork Facing and Release Agents," *Symposium Sichtbeton—Planen, Herstellen, Beurteilen, 2nd Symposium Baustoffe und Bauwerkserhaltung,* Karlsrue University, Mar. 17, 2005, pp. 45-56.

Includes a summary of *DBV Merkblatt Sichtbeton Deutscher Beton- und Bautechnik-Verein e.V, 2004* [Exposed Concrete Guide to Good Practice 2004] as follows:
This guide compares exposed concrete deficiencies [including surface porosity] with respect to the current state of the art, as:

- either avoidable or partially avoidable, and
- not (yet) avoidable

The quality requirements with respect to porosity are shown in the following table.

Tab.2: Detailed information on the quality criterion "porosity"

Porosity class	P1	P2	P3	P4
Maximum pore fraction[1] in mm^2	3000	2250	1500	750
Maximum pore fraction with respect to a test surface 500 x 500 mm^2	1.2 %	0.90 %	0.60 %	0.30 %
[1] Pore diameter 2 < d < 15 mm				

The following quote indicates that compliance with porosity classes P1 through P4 was not reliably achievable in 2005 when the paper was published:
"…requirements are applied to exposed concrete that, according to the current state of concrete technology, are not achievable in a technically reliable manner. These requirements include:

- Uniform colour shade of all visible surfaces on the structure
- Visible surfaces without pores
- Compliance of the pore area fractions with porosity classes P1 to P4
- Uniform pore size and distribution within an individual area and in all visible surfaces on the structure
- Efflorescence-free visible surfaces of in-situ concrete
- Uniform colour shade and texture of the concrete surface and formwork joints.
- Sharp edges without small break outs and efflorescence
- No clouding and mottling.

Deviations from these are regarded as deficiencies whose root cause lies in insufficient knowledge of interfacial interactions between fresh concrete, the type of release agent and the organic polymer coatings on non-absorbent formwork surfaces."

Research using optoelectronic image analysis is cited indicating that widely differing porosities result from the use of formwork panels with one surface class-e.g. phenolic resins—and the same reference concrete. The authors state that:

"…this means that, depending on the selected material of the formwork facing, it is possible to produce exposed concretes with three porosity classes (P2 to P4) from the same concrete mix."

Houston, B.J., "Methods of Reducing the Size and Number of Voids on Formed Concrete Surfaces", Technical Report no. 6-788, Vicksburg, Miss., U.S. Army Engineer Waterways Experiment Station, July 1967. 35 p.

This laboratory research is of limited value today because the concrete mixes studied were relatively stiff (normal workability: 2-1/2-in., low workability 1-3/4-in., and high workability: 4-1/2-in.), SAE 30 oil was brush-applied to the forms, and many current form sheathing surfaces weren't available in 1967.

The results are interesting, though, because it reports one of the first attempts at a quantitative evaluation of bugholes in laboratory tests. Surface voids were counted and grouped according to the following sizes:

b. 1/8- to 1/4-in. dia. b. 1/2- to 1-in. dia. c. Over 1-in. dia.

Because larger voids create a more unsightly appearance than smaller ones, a weighting system based on surface area of the voids was used in a statistical analysis of lab tests. The a.-group voids had a weighting of 1, with b.-group having a weighting of 6 and c.-group a weighting of 23. The factors of 1, 6, and 23 were multiplied by the number of voids in the respective size groups and results were summed to obtain weighted totals.

The results indicated that:

- High air contents and high and low water contents *may* increase incidence of surface voids, but results were not [statistically] conclusive.
- Voids on vertical surfaces can be reduced to an acceptable level by proper and sufficient vibration, but this was not necessarily true for sloping form surfaces
- Smooth, slick form coatings may be beneficial in reducing voids, but their influence is small compared to other factors.
- Parting oils [barrier-type form release agents] had a limited value in reducing surface voids.

Hurd, M.K., "Avoiding Arguments Over Architectural Concrete", *Concrete Construction*, 1990, pp. 759 – 766.

Article states that: "…it is virtually impossible to do vertical cast-in-place work that is completely uniform in color and free from bugholes." Includes photos from a form release manufacturer showing that thinner films of form release reduce the size and frequency of bugholes.

Hurd M.K., *Guide for Surface Finish of Formed Concrete: As-Cast Structural Concrete,* ASCC Education and Training Committee, Aberdeen Group, 1999 26 pp.

Written when ACI 301 included the terms "rough- and smooth-form" finishes. Discusses fins, offsets, bugholes, tie holes, and honey comb. Includes photos of concrete surfaces showing a range of bughole size and frequency in as-cast surfaces. Also shows photos taken from about 15 to 20 ft and close-ups of the same areas.

Johnson, W.R., "The Use of Absorptive Wall Boards for Concrete Forms," *Journal*, American Concrete Institute, June 1941, p. 631.

One of the early uses of permeable formwork in large-scale construction (Over 200,000 sq ft of absorptive form liners at Kentucky Dam). Summary and Conclusions: 1. Practically all voids and pits, always found on formed vertical and sloping surfaces, are eliminated.

Johnston, David W., *Formwork for Concrete 8th ed., SP-4*, American Concrete Institute, 2014, p. 4-20, and pp. 13-1 through 13-14.

Includes a new chapter on Formed Concrete Surface Quality with an overview of ACI 347.3R-13. States that ACI 347.3R-13 is: "…available for specifiers to use when converted to mandatory language."

Quotes:

"Voids with a diameter less than 3/32 in., or less equivalent area than a circle of that diameter, are not counted. If voids have a diameter of D_{max}, or greater equivalent area, the surface is evaluated and a procedure is developed for repair of the deviation."

"Highly absorptive materials used a form liners have eliminated voids and air pockets on the surface of concrete…" "However, increased cost and difficulties associated with the use of such materials have prevented their widespread acceptance."

Klovas, Albertas, Dauksys, Mindaugas, and Levulis, Linas, "The Distribution Analysis of Hardened Horizontal Surface Air Pores," *Journal of Sustainable Architecture and Civil Engineering,"* No. 2, 2013, pp. 40-45.

Summarizes factors affecting surface quality of concrete and presents data on the effects of excessive form release agents on five differing horizontal form surfaces of the sizes noted:

- Wood impregnated with polymeric oil [WPO]: 550 x 300 mm;
- Wood covered with rubber [WCR]: 400 x 400 mm;
- Sawn timber formwork [ST]: 600 x 300 mm;
- Plastic formwork [P]: 400 x 400 mm;
- Metal formwork [M]: 400 x 400 mm.

Concrete with a w/c of 0.54, flow table value of 525 mm, and air content of 4.0% was placed in forms on a vibration table and vibrated 7 seconds.

Based on photographs, ImageJ freeware was used to calculate the area of surface blemishes (bugholes) in a total area of about 900 cm^2. Results are shown in Table 5. N = no. of voids, M = mean value, D = dispersion, SD = stand. Dev., CV = coef. of var., MIN = minimum void size, MAX = maximum void size, and RF/I = relative frequency/interval[dimensional range]

Table 5. Statistical analysis of the experimental results

	Formworks				
Parameters	WPO	WCR	ST	P	M
N	59	106	12	45	70
MV	4.203	4.155	4.867	1.728	2.133
D	3.665	6.305	9.683	0.456	0.535
SD	1.914	2.511	3.105	0.675	0.732
CV	0.456	0.604	0.638	0.391	0.343
MIN	1.784	1.499	1.721	1.065	1.033
MAX	11.230	17.82	12.868	4.717	4.65
RF/I	0.322/ [3.157; 4.530)	0.557/ [1.45; 3.50)	0.500/ [3.95; 6.18)	0.556/ [1.065; 1.627)	0.314/ [1.54; 2.048)

Wood covered with rubber formwork produced the most porous surface because it did not absorb the excess form release agent, and sawn timber formwork produced the least porous surface because it absorbed the excess form release agent.

Klovas, Albertas, and Dauksys, Mindaugas, "The influence of form release agent application to the quality of concrete surfaces", *IOP Conference Series Materials Science and Engineering*, November 2013.

A study of concrete surface quality changes caused by use of different form release agent applications. Concrete surface blemishes [bugholes] were evaluated using a combined method described in CIB Report No. 24 "Tolerances on blemishes of concrete" and GOST 13015.0-83 [See Klovas and Dauksys, "The Evaluation Methods of Decorative Concrete Horizontal Surfaces Quality", *Materials Science*, Vol. 19, No. 3, 2013] and an image analysis process: "ImageJ." Two different concrete compositions were used: BA1 (low fluidity [525 mm flow], vibration is needed) and BA8 (high fluidity [720 mm flow], vibration is not needed). Three castings with each of four differing form facings on mold soffits for horizontal specimens, and one vertical form with facing made of wood impregnated with polymeric oil. Water emulsion based form release agent was used with differing applications (normal and excessive).

Some of the data seems to be from previous work done by Klovas, Dauksys, and Linas. The high flow mixtures resulted in fewer bugholes on the horizontal specimen soffits than were noted in the previous work.

For CIB Report 24 classes 1, 2, and 3, ImageJ analysis of the vertical form faces indicated bughole area percentages [SVR] of 0% –0.1%; 0.1%-0.3%; and 0.3%-0.5%, respectively.

Klovas, Albertas, and Dauksys, Mindaugas, "The Evaluation Methods of Decorative Concrete Horizontal Surfaces Quality", *Materials Science*, Vol. 19, No. 3, 2013.

One of the goals of this article was measuring blowholes on concrete surfaces and classifying the surfaces in accordance with visual appearance based on:

- Reference photos in CIB Report No. 24,
- The largest dimension of the blowholes as indicated in GOST 13015.0-83 and,
- The authors' proposed image scanning method using "ImageJ" freeware, which permits calculating a ratio between blowhole area and the total area of the scanned image [SVR].

Three different concretes were studied: BA1, BA7 and BA8. Mix proportion are given in the article. Also, five different formworks were used: wood impregnated with polymeric oil [WPO], wood covered with rubber [WCR], sawn timber [ST], metal [M] and plastic [P] formworks. The following parameters for [SVR] were calculated: mean value, dispersion, standard deviation and the coefficient of variation. Also maximum and minimum values of experimental results are given. Intervals of the experimental results are provided for each specimen with the biggest possibility.

Table 4 from the article shows how concrete surfaces are evaluated for blemishes [blowholes] by CIB 24 for four different surface classes.

Table 4. Consideration of the blemishes

Blemishes considered	Classes			
	Special	Elaborate	Ordinary	Rough
Distributed holes	0–2	2–4	4–6	No requirement

GOST requirements and explanatory information are as follows:

Table 5. Requirements for the concrete surface quality by GOST 13015.0-83

Categ. of concrete surface	Diameter or the biggest dimension of the blemish	Dimensions of the local rises and cavities	Wreckage depth of the edge	Total length of the wreckages
	Data, mm			
A1	Very smooth surface (reference)		2	20
A2	1	1	5	50
A3	4	2	5	50
A4	10	1	5	50
A5	No require.	3	10	100
A6	15	5	10	100
A7	20	No require.	20	No requir.

Note that:

- Class A2 concrete surfaces allow one blowhole with a diameter or largest dimension of 2 mm, both per m^2;
- Class A3 concrete surfaces allow one blowhole with a diameter or largest dimension of 6 mm, both per m^2;
- Class A4 concrete surfaces allow one blowhole with a diameter or largest dimension of 15 mm, both per m^2.

For image analysis, photos of the concrete surfaces were at about a 30 cm distance and imported into the ImageJ program. Methodology for this and the ensuing analysis is explained.

Based on results of the research, Table 8 shows a comparison of how the test surfaces would have been categorized in accordance with GOST, CIB 24, and [SVR] based on ImageJ analysis.

Table 8. Combined concrete category diversification

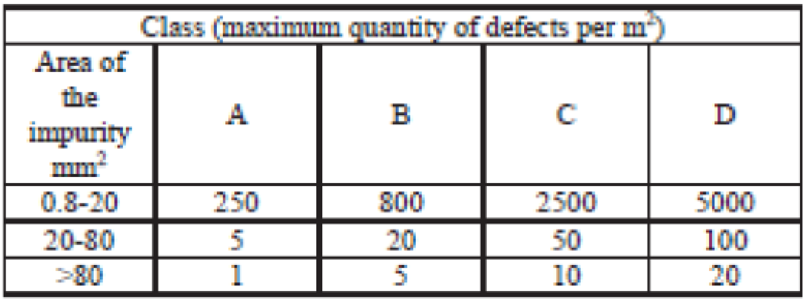
According to methods	Class of the concrete			
	Special	Elaborate	Ordinary	Rough
GOST 13015.0-83, categories	A1 – A2	A3 – A4	A5 – A6	A7 >
CIB Report No. 24. marks	0 – 2	2 – 4	4 – 6	No req.
ImageJ, bugholes area, %	0 – 0.1	0.1 – 2	2 – 4	13 >

The authors recommend using SVR as measured by the ImageJ approach to classify surfaces more precisely and with less ambiguity.

Klovas, Albertas, and Dauksys, Mindaugas, “The Insights of Formed Concrete Surface Quality Evaluation Using Open Source Software Image J”, *Proceedings of the 4th International Conference Advanced Construction*, October 2014.

Lists several causes of surface “impurities’ [including blowholes] based on cited literature. Specimens were made using two concretes with flow values of 525 mm and 720 mm, but details on the specimen shape and size and consolidation methods are not given in this paper. Detailed descriptions are given for the method by which formed surfaces were analyzed using ImageJ software. The surface quality was determined using the Nordic Concrete Federation system shown in Table 4.

Table 4. Concrete quality classes of surface



Class (maximum quantity of defects per m^2)				
Area of the impurity mm^2	A	B	C	D
0.8-20	250	800	2500	5000
20-80	5	20	50	100
>80	1	5	10	20

Of the two concretes tested, the low-flow concrete containing a lower cement content and only a superplasticizer met Class D requirements, and the higher flow concrete which contained a higher cement content and a different superplasticizer plus viscosity modifying and anti-foaming admixtures met Class C requirements.

The authors concluded that:

- ImageJ analysis would be more useful if it provided not only the total area of blowholes, but the largest blowhole dimensions.
- The use of more fine particles (higher cement content), and viscosity modifying and anti-foaming admixtures could have determined the surface quality differences between the two concretes.

Klovas, Albertas, and Dauksys, Mindaugas, “The Influence of Admixtures on the Technological Properties of Fresh Concrete Mixture”, *Materials Science*, November 2015.

Paper gives data for fresh concrete properties of superplasticized concretes made with varying amounts of anti-foaming, viscosity modifying, and air-entraining admixtures. The anti-foaming and viscosity modifying admixtures were not useful in reducing the entrapped air content of concrete made with the superplasticizers. No measurements of surface quality were made, but the authors stressed the importance of concrete yield stress in determining risk of blowholes.

Klovas, Albertas, “The Influence of Concrete Mixture’s Rheological Properties on Formed Monolithic Concrete Surface Quality and Its Evaluation”, Summary of Doctoral Dissertation, Kaunas University of Technology, 2016, 34 pp.

Includes a review of different methods for concrete surface quality evaluation. Draws conclusions regarding the effects of concrete rheological properties on formed surface quality but with no experimental data connecting the rheological properties with surface quality. Conclusions [paraphrased]:

1. On the basis of a systematic analysis of scholarly literature there is lack of scientific information on modifications in concrete mixtures needed to obtain high quality surfaces. Most of the widely available surface quality evaluation methods are actually based on subjective opinion which is not reliable when classifying surfaces according to their quality.

2. The image analysis method (software *BetongGUI 2.0*) easily allows measurement of the quantity and the largest dimension of surface air pores. This data [from samples] allows concrete surfaces to be classified according to their quality levels by [estimating] areas of blemishes in the entire surface of tested specimens.
3. Concrete yield stress and plastic viscosity were significantly reduced by increasing the ratio of coarse and total mixture aggregate from 0.32 to 0.52. Surface blemishes sized 10 to 15 mm were reduced from 148 to 117 units, while larger blemishes measuring >15 mm were reduced from 96 to 37 units. [No data given.]
4. Increasing fine particles (cement together with sand not exceeding 0.25 mm size) from 441 to 600 kg/m^3 significantly reduced the mixture's yield stress and its plastic viscosity. It also significantly reduced the ratio between the areas of surface blemishes and the total specimen size from 17.3 to 0 %. [No data given.]
5. An increase in superplasticizer dosage to 1.2 % of cement significantly reduced the mixture's yield stress and its plastic viscosity while the W/C ratio was steady. The ratio of blemishes was reduced from 0.37 % to 0.28 % [No data given.]. An increase of the viscosity modifying admixture up to 1.1 % did not significantly influence the mixture's rheological properties. On the other hand, it reduced the number of the differently sized surface blemishes. 10-15 mm blemishes were reduced from 157 to 14 units while >15 mm size defects were reduced from 44 to merely 1 unit [No data given.].
6. An increase of the air-entraining admixture dosage resulted in decreased yield stress and plastic viscosity values. It also had a positive influence on the formed concrete surface quality [No data given.]. This kind of admixture does not allow bigger pores to emerge while smaller pores are less visually noticeable. The utilization of anti-foaming admixtures did not exhibit a noticeable influence on the mixture's rheological properties although it reduced the number of 10-15 mm sized air pores from 157 to 24 units and >15 mm pores from 44 to 3 units per 1 m^2 [No data given.].
7. The dependence between concrete surface blemishes and different constituents of the mixture can be expressed by a parabolic relation. Only the dependence between surface blemishes and the fine aggregate can be expressed according to an exponential dependence. Correlation coefficients in most cases show strong relations between the variables.
8. Based on the obtained results, concrete slump alone cannot be linked with the formed concrete surface quality [No data given.]. Concrete surface quality is affected by many different variables: the quality and application of formwork; the type of form release agent and its quantity; the agent's application; the appropriate technology of mixture compaction and, finally, the human factor. It must be stressed that varying amounts and types of mixture components have the largest influence on concrete surface quality [No data given.].

Lemaire, Gruillaume, Escadeillas, Gilles, and Ringot, Erick, "Evaluating concrete surfaces using an image analysis process", *Construction and Building Materials*, 2005, pp. 604-611.

Conflicts exist between owners, architects, and general contractors regarding the extent and quantity of bugholes because the CIB Report 24, AFNOR P18-503 standard in France and the NBN B 21-601standard in Belgium involve subjective judgments. The authors use ImageJ analysis of photos to more objectively analyze both differences in color and size and frequency of bugholes. Photos are taken close enough to distinguish detail of about one square millimeter. A "large number of zones" were measured for color comparisons [many samples]. Images of photos illustrating the seven surface classes in CIB 24 were analyzed by determining the number of bugholes/m^2 and bughole area as a percent of total area [equivalent to SVR in ACI 347.3R-13]. Fig. 13, below, indicates that

CIB Classes greater than 3 have SVRs exceeding the maximum allowable value of 1.2% for an SVR1 in ACI 347.3R-13. This would place them in the CSS1 category which applies to concrete surfaces in areas with low visibility or of limited importance with regard to formed concrete surface requirements, used or covered with subsequent finish materials.

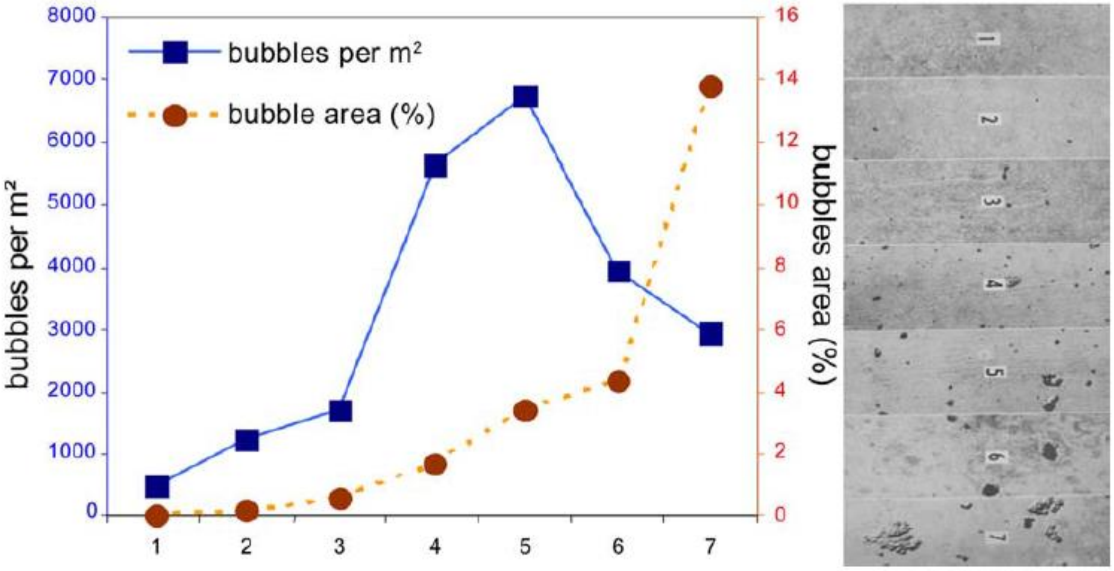
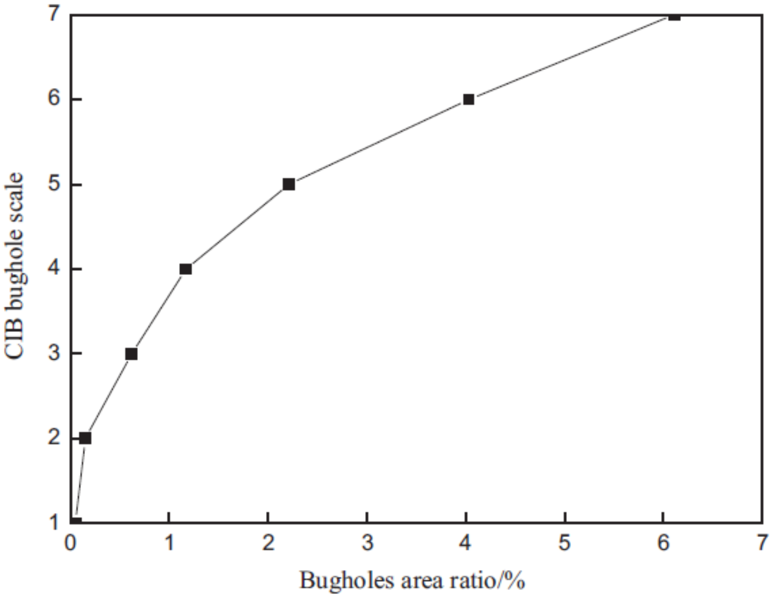


Fig. 13. Bubble board [2] and its characteristics measured by image analysis.

Liu, Baoju, and Yang, Tengyu, “Image analysis for detection of bugholes on concrete surface,” *Construction and Building Materials,* No. 137, 2017, pp. 432-440.
This paper established a method for detecting bugholes on concrete surfaces using image analysis. The method is based on the image processing toolbox of MATLAB. Image gray, contrast enhancement, and Otsu’s image threshold segmentation technology are used to extract the characteristics of bugholes on the concrete surface. A threshold value of shape characteristic coefficient (chosen as 45—similar to aspect rario) distinguishes between cracks and bugholes. A relationship between the CIB scale and the area ratio of bughole is established, as shown below.



This relationship is similar to ones published by **Lemaire et al (2005)** and **Silva et al (2011)**. The authors propose recommended requirements for bughole classification that include a maximum diameter. Their digital image method requires a 40 cm focus distance for a detection accuracy of 0.1 mm. For large-size concrete members, the focus distance can be controlled at 50–200 mm, and a sufficient number of photographs must be taken for analysis to ensure the representativeness of the experimental results.

Linder, R., "Pores, blowholes, wood inclusion in fair faced concrete surfaces, coatings and floor surfaces. Part 1. *Betonwerk & Fertigteil Technik*, v. 58, no. 5, May 1992, p. 67-74.

> **Excerpts:**
> The dynamic conditions during, start-up, operation, and switch-off of compaction apparatus with changing frequencies and amplitudes, and the natural frequency [of concrete]—resonance and interference phenomena are so complex, that no practicable laws on concrete compaction are currently available; empirical values, that can be only conditionally applied, are all we have. In particular the tendency to pore formation and the frequency and distribution of the pores are difficult to predict. Non-air-entrained concrete is regarded as having been well compacted and closed-textured when the air content ranges between 1% and 2% by volume, a relative fluctuation of 100%.
> Air voids occur in the core of the concrete structure in about uniform distribution and to a lesser content than in the edge zone, where the cement paste and fine cement mortar contents are much higher, keeping the tiny air bubbles from rising and exiting.
> An especially high number of pores can be expected in concretes
> — of high consistency and a small content of excess fines in the aggregate mix of, most often, especially viscous fresh concrete;
> — with high water-cement ratios (rapid liquefaction encloses the pores);
> — with a high reinforcement content, particularly with large-diameter closely spaced bars; and
> — with a low concrete cover over the reinforcement, in particular with aggregate mixtures whose maximum particle sizes exceed the thickness of the concrete cover.
> The perpendicular edge zones of walls, columns and uprightly manufactured precast components are, compared to other areas, affected to a much higher degree than the upper unformed sides, because here the bulk material layer tends to be higher and the distance on the way up along the form facing material longer, due to the additional friction: Smooth, dense, wet, hard and rigid forming panels as well as water-repellent and thickly applied release agents result in more porous concrete surfaces than textured, porous, hygroscopic and soft facing materials onto which the emulsifying release agents are thinly applied.
> Linder, R., "Pores, blowholes, wood inclusion in fair faced concrete surfaces, coatings and floor surfaces. Part 2," *Betonwerk & Fertigteil Technik*, v. 58, no. 6, June 1992 (b), p. 70-76.

Excerpts:

6.4.2 Evaluation standards for the pore structure

The term pore structure defines the given bandwidth of size, frequency, and hole distribution which can be barely discerned by the naked eye from the usual reading or writing distance and further away. The pore structure fluctuates the most:

--In thick lifts at the top of which more and larger compaction pores will be formed than in thinner lifts.
-- in concrete components placed in battered forms
-- alongside leaky abutting formwork elements and where the form facing material has been patched
-- on the upper edge of concrete components
-- in stiffer concrete consistencies much more readily than in soft ones.

Bugholes are only discussed in instruction sheets, states in sibylline [divine revelations in a frenzied state] German legalese:
“The absence of, in particular, the following properties shall not preclude satisfaction of the contractual performance (fair-faced concrete)
…totally uniform pore structure (pore size, pore distribution).” It thus remains open to what extent the size, the frequency, and the distribution of the visible pores are allowed to fluctuate. An indirect aid in deciding on the justification of a claim are the following formulations:

“A good aid is to refer to comparable sample components or already completed works” and “Fair-faced concrete shall be evaluated in the condition of use and from a reasonable distance (in relationship to the size of the surfaces and the type of building viewed).”

“The sample components or existing works can be likened to the surface observed only provided it was executed under largely similar conditions (dimensions, initial reactants, concrete composition, formwork, processing, curing, weathering, age of concrete etc).

Reference 11 states simply: “During concrete compaction, small amounts of air and water inclusions, occurring on the, fair-faced concrete surface as pores, cannot be avoided.” With regard to the sample piece [mock-up], the formulation is the same as in Reference 10.

A reasonable distance [for evaluation of formed surfaces] is often assumed to be the height of the building. A close-up evaluation standing near the scaffolding is surely false.

Even if apparently VOB-complying “unambiguous and detailed” specifications have been provided there still remains considerable latitude for making a discretionary decision, ending up in the final “classification” given in Reference 10: “Any property of the exposed formed surface that can only be evaluated based on subjective criteria may not be elevated to claim status in the sense of the contract for work and services."

While fair-faced concrete standard 18217 (concrete surfaces and form sheathing) does not stipulate the amount of pores permitted, the relevant standard commentary makes it clear that it is the duty of the contractor to make known any misgivings he might have based on VOB-B § 4 sub-para. 3, if the specifications require a concrete surface void of pores, as such a requirement could not realistically be achieved with the present state of the art available and can thus not be warranted.

An Austrian version (of specifications) [Huber, G.: Sichtbeton, Hersusgeber: Verein der osterr. Zementtabrikanten, Wien 1979] suggests that where "high requirements" must be met and formwork with water barrier or absorbing properties are utilized, the maximum diameter of pores should not exceed 15 and 10 mm, respectively. *On a test surface of at least 50 x 50 cm*^{2} *a content of 0.3 percent of pores above 1 mm diameter on the test surface is regarded as realistic.*

A paper that appeared in 1970 [Heiermann, W.: Gewahrleistungsprobleme bei Sichtbeton, Bauwirtschaft 1970, H. 38] and which received considerable attention observed on the subject of "undesirable pore patterns," that the demand for a low-profile and uniform pore pattern could not be met with the present state of the art and would thus constitute as contractual performance that was technically impossible to achieve and therefore legally ineffective and not subject to any warranty. A paper that appeared in 1975 supplements this point of view by referring to the already mentioned obligation of the contractor. Since then, there have been no new findings on the subject of concrete technology and abilities.

The report of an International Commission [CIB Report 24] names four quality categories for fair-faced concrete. There are no requirements on pores in the lowest category; for the remaining ones, a seven-level scale with an increasing number and size of pores is provided. Here, not only maximum permissible values are given but among other things the demand made that the pore pattern for adjacent or spaced-apart areas may differ by a varying number of levels on the scale. This stipulation appears to be rather "academic"; it is not discussed in professional circles and though updated since then, rarely applied in practice.

An information sheet on precast concrete components refers to pores as being "unavoidable." Cast in-situ components, due to the way they are manufactured, are bound to have more pores and exhibit greater differences in pore structure than precast components, especially near the top of individual concrete layers and concrete components and in the vicinity of construction and settlement joints. Claims will increase accordingly. For this reason it is advisable to abstain from sandblasting fair-faced in-situ concrete components.

Litzner, Hans-Ulrich, and Goldammer, Klaus-Reiner, "Philosophy of the New Guide to Good Practice for Exposed Concrete from the DVB/BDZ," Beton-und Stahlbetonbau, 100 (2005), Vo. 6, pp. 489-495.

This article is a description of the DVB/BDZ Guide that for the first time defined four classes of exposed concrete, and was the basis for ACI 347.3R-13. Litzner and Goldammer state that information in the Guide is based on practical experience that was gained in recent times with prestigious structures made of exposed concrete. The Guide was presented at a joint conference at which a Munich architect gave the keynote address titled “Building with Exposed Concrete—a Great Unhappy Love Affair,” and covers conflicts described by the architect. The Guide’s intent is promoting the use of exposed concrete as a means of expression in modern architecture and reducing the reasons for unhappiness by architects. The article authors state that: “[The reasons] lie in the different expectations of the participating partners (in the construction process), incomplete or even no communication, and a lack of understanding for the position of others.” They add that the reasons were primarily due to the absence of any unambiguous German standards and definitions regarding exposed concrete technology—a problem they say the Guide solves.

Recommendations in Tables 1 and 2 from the DVB/BDZ Guide that are included in the article are very similar to those Tables 3.1a and 3.1d in ACI 347.3R-13. A photo shows workers tracing surface voids onto a piece of Mylar, but no detail is given for the sampling and measurement methods used in determining SVR. Table 3 from the DVB/BDZ Guide gives design and construction requirements for improving color uniformity. There are no tables similar to Tables 3.1b and 3.1c in ACI 347.3R-13 in the article.

The article includes the following statements regarding acceptance and evaluation:

- Overall appearance of a visible surface is the fundamental acceptance criterion for the agreed exposed concrete class. Slight irregularities, e.g. in the texture and color, are characteristic in all exposed concrete classes.
- When evaluating exposed concrete surfaces, the overall impression from the usual viewing distance is decisive. The following viewing distances have proven effective in practice:
  - Structure: An adequate distance corresponds to the distance that allows the essential parts of the structure to be viewed and the decisive design characteristics must be discernible.
  - Components: An adequate viewing distance is that at which the viewer stands during normal use.
  - Individual criteria are only inspected if the overall impression of the visible surfaces does not correspond to the agreed specifications. If evaluation of individual criteria is necessary, this should be carried out with respect to the particular component.

These statements are in agreement with similar one in ACI 347.3R-13. Note that this article mentions architectural concrete in several instances and thus implies that the DVB/BDZ Guide is intended for use with architectural concrete.

Malone, Phillip, “Use of Permeable Formwork in Placing and Curing Concrete”, Technical Report SL-99-12, US Army Corps of Engineers, October 1999.

Bug holes in concrete surface are generally thought of as producing aesthetic problems rather than problems related to durability. Surface irregularities such as bug holes can affect performance in structures where running water and suspended materials abrade the surface of concrete because they may induce cavitation and the formation of eddies that concentrate the wear on specific points on the surface. If it is necessary to reduce the number of bug holes, there are few useful options beyond using permeable formwork. Bug holes can be reduced by placing concrete in more fluid condition (high-slump concrete); however, typically, the surface of the high-slump concrete will be less dense than with low-slump concrete and there will be a greater chance of scaling from freezing and thawing action (Reading 1972).

The ability of the permeable formwork to reduce the number of bug holes is obvious from inspection and has been clearly documented. Marosszeky et al. (1993) measured the relative areas of bug holes and smooth surfaces on blocks of concrete cast with and without permeable formwork. Blocks cast with conventional formwork have 0.59 to 1.5 percent of the surface area involved in bug holes. Surfaces on blocks cast against permeable formwork have less than 0.1 percent of the area in bug holes. Richardson (1994) reported that permeable liners were found useful in reducing the number of bug holes in concrete placed against inclined surfaces and also reduced the number of voids that typically form just below the concrete surface in inclined forms.

The architectural merits of concrete cast with permeable formwork have generally not been emphasized in recent studies because permeable formwork may produce a mottled gray and dark gray surface. The surface will be virtually bug hole-free, but may not have a uniform color (Farahmandpour 1992).

Marosszeky, Marton, et al, “Textile Form Method to Improve Concrete Durability,” *Concrete International,* Nov. 1993, pp. 37-39.

A laboratory study of the effect of a textile form liner on concrete surface properties, one of which is the presence of bugholes. Two types of specimens were cast; one with a sloping form surface (half covered with textile liner—Type I) and the others (Type II) with both sides of the form vertical. One side of the form surface was covered with a textile liner, with the other side being a conventional form (see Fig. 2). [”Conventional” was not defined in the paper and we got no reply from the lead author when we asked for more detail on the form surface.] Ready-mixed concrete 28-day strength ranged from 1500 to 5800 psi but there is no further information as to the effect of strength [w/c] on the area of bugholes. The fine aggregate was river sand with a low fineness modulus (2.2) and coarse aggregate was basalt with a maximum size of 20 mm. Concrete was transferred by hand directly from the truck discharge chute into the forms and vibrated in four layers. [No details about vibrator used or duration of vibration.] Samples for bughole measurements were 200x200-mm squares at the upper, middle, and lower regions of each face of Test Block 1 (Type I) and Test Blocks 2,3, and 4 (Type II). Bugholes at each location were traced on a transparent sheet and area of each was calculated as the width x height. The total area of bugholes was divided by the sample area and expressed as a percentage, similar to the method used for SVR calculations. Results are shown in Fig. 3. For sloping forms with no textile liner, SVR was about 1.5% and for vertical forms with no textile liner SVR ranged from about 0.5% to about 1.1%. Quantitative image analysis was also used, but the results were used only to show that textile forms significantly reduced SVR.

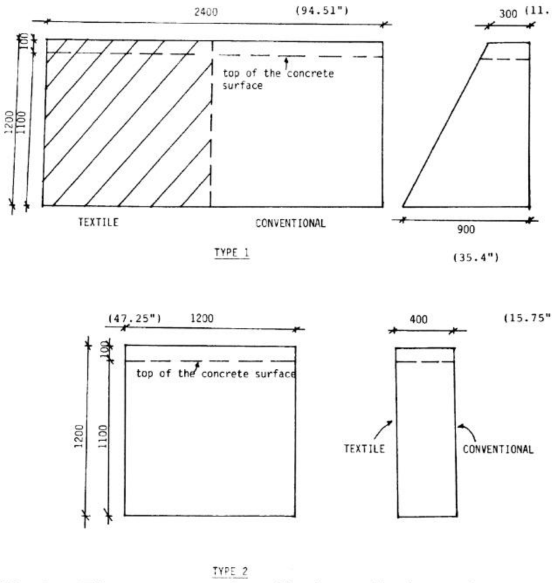


Fig. 2 — The two types of test block used in the study.

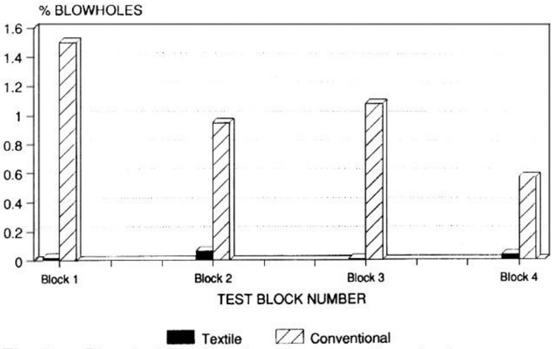


Fig. 3 — Blow hole ratio using the manual method.

Moruza, Gail M., and Ozildirim, H. Celik, "Self-Consolidating Concrete in Virginia Department of Transportation's Bridge Stuctures," *ACI Materials Journal,* Jan-Feb. 2017, pp. 57-64.

Two issues regarding bugholes are discussed. Using handheld buckets rather than pumps at some locations did not provide enough head pressure to move the SCC. This slowed the placement, thus causing a reduction in flowability and the SCC's natural ability to consolidate itself. Because of a reduction in flowability, voids were left at the base of these placements. To reduce bugholes in precast bridge beams, higher slump values were required. However, this created a tradeoff that presented the risk of lower mixture stability. Care was exercised to use the target value and avoid slump flow values close to the high or the low limits of the specification. Proper use of fine materials and viscosity-reducing admixtures helped to keep the SCC stable.

NPCA Quality Control Manual for Precast Concrete Plants, 12th ed., National Precast Concrete Association, July 2015, pp. 54, 61, 63.

When using self-consolidating concrete in intricate formwork or formwork containing heavy reinforcement or blockouts, precast producers may find that light vibration or tapping of the forms will allow for the concrete to be fully compacted. This can eliminate the problem of bugholes.

Formed surfaces shall be considered satisfactory if they are relatively free of bugholes, unless the surfaces are required by design to be finished. A minor number of voids on the surface is quite normal. Filling of these voids is done for cosmetic purposes and usually only when required by specifications.

Post-pour inspections shall document excessive bugholes. Defects not impairing the functional use or expected life of a precast product shall be considered minor defects. Minor defects shall be repaired by any method that does not impair the product. Repairs of minor defects are essentially cosmetic, (e.g., the product would behave as intended without the repairs).

Ozkul, Tarik, and Kucuk, Ismail, "Design and optimization of an instrument for measuring bughole rating of concrete surfaces," *Journal of the Franklin Institute*, No. 348, 2011, pp. 1377-1392.

A theoretical, but not yet operational, device for measuring bugholes is based on how much pressurized gas is allowed to escape from a container with a skirt that crosses the bughole. Only bugholes crossed by the skirt, with some area inside and outside the skirt are measured. *Simulation* of the device operation is done by overlaying a skirt pattern over a reference of photo concrete surfaces from CIB 24, then measuring the lengths in mm of bughole edges that appear as dark patches covered along the skirt channel. The skirt pattern is slid over the reference photo and measurement is repeated at least four times. The average length is related to the seven surfaces used as reference samples in CIB 24.

It is interesting to note the following passage in Section 1.1, Recommendations to alleviate the bughole problem:

> "Being considered a major problem, construction industry paid careful attention to techniques and practices to reduce amount of bughole during the casting process. There are numerous researches conducted for different methods, from use of special forms and liners to cast concrete [8,9] to the effective use of vibrators for settling concrete inside the forms [10,11]. Research is also done on use of special types of concrete to use and admixtures to mix with the concrete before the concrete is poured into the forms [12–23]. As a result of these researches, construction industry has developed number of procedures and recommendations to reduce sources of bugholes during the manufacturing process [24,25]. Although the methods mentioned above are effective in reducing the number of bugholes, none of the methods are really expected to get rid of bugholes problem completely. <u>In most cases, reducing the surface void area contributed by the bugholes to 1% is considered a successful goal in bugholes reduction."</u> [underlining added].

Ramsburg, Paul, "The Effects of Form Materials and Release Agent Types on the Appearance of Self-Consolidating Concrete, 2004 CBC.

Deals with use of SCC in precasting operations, and the effects of form materials and release agents on bughole formation. A study, apparently made on 4-ft thick precast specimens (p. 6), compared results when using plywood, marquisate-surfaced steel framed panels, and steel in contact with the concrete surface. Results indicated that new plywood sheathing in good condition initially produced the best appearance, but after the first casting showed signs of wear, which produced a slightly less defect-free surface. Subsequent castings resulted in more defective appearance than steel. Observations indicated that cement paste buildup on each forming material made surface appearance worse and rusted areas on steel forms, at times, produced more surface voids than were noticeable on vibrated conventional concrete. When the form skin was colder than the SCC, it was noted that more small bugholes were visible on the concrete surface.

Steel forms cleaned of rust with a wire brush wheel on an electric grinder still produced unacceptable panels. Removing mortar buildup in the same manner greatly improved concrete surface appearance except for one instance when the steel form was gouged. The gouge mark resulted in bugholes.

Five release agent varying in type—barrier, vegetable, and three petroleum-reactive types—were included in the study. Barrier types required heavy application rates that increased the presence of bugholes. When used on plywood, the vegetable agents provided only slightly better results than two of the reactive agents. Ranking of the surfaces was based on a zero to three scale as indicated in the table title Product Appearance.

Forms must be in good condition also, and the Virginia Department of Transportation suggested a way to quantify an acceptable level of form condition as shown in the table titled Form Conditions.

Conclusions were as follow:

- Any defect in the forming system will become extremely visible when using well-developed self-consolidating concrete. A smooth surface will exaggerate the appearance of marks left in the concrete product from scratches, rust pits, concrete paste buildup, or other defects.
- Barrier type release agents should not be used with SCC if the finish is important. When applied in thin coats, the forms don't release easily from the concrete and may peel the surface. When applied heavily, the barrier agents trap large amounts of air pockets.
- When selecting a reactive release agent, mockups should be cast to ensure that the agent performs well with the SCC being used. All reactive release agents do not perform equally well with SCC.

	PRODUCT APPEARANCE
0	SMOOTH DEFFECT FREE SURFACE SOME MINOR PINHOLES (-1/16")
1	MINOR PINHOLES (-1/16") SOME AREAS OF SMALL BUGHOLES (1/8")
2	MANY SMALL BUGHOLES (1/8") SOME LARGE BUGHOLES (+1/2") MINOR SPOTS OF RASH
3	MANY LARGE BUGHOLES (+1/2") LARGE AREAS OF RASH

	FORM CONDITIONS
0	SMOOTH DEFFECT FREE SURFACE
	NO CONCRETE BUILDUP
	RELEASE AGENT APPLIED LIGHTLY AND EXCESS WIPED AWAY
1	MOSTLY SMOOTH SURFACE MINIMAL ISOLATED DEFFECTS
	ISOLATED AREAS OF LIGHT CONCRETE BUILDUP
	RELEASE AGENT APPLIED LIGHTLY WITH SOME AREAS OF EXCESS
2	SEMI-SMOOTH SURFACE WITH PATCHES OF PITS AND SCORING
	LARGE PATCHES OF CONCRETE BUILDUP
	MODERATE APPLICATION OF RELEASE AGENT WITH AREAS OF EXCESS
3	ROUGH SURFACE WITH DEFFECT AND RUST PITTING
	CONCRETE BUILDUP AT +1/16" IN AREAS
	RELEASE AGENT APPLIED HEAVILY - DRIPPING AND POOLING

Ramsburg, Paul, "Using SCC to Battle Bugholes," *Concrete Construction*, November 2015. (Posted on Concrete Construction Network Dec. 21, 2005 http://www.concreteconstruction.net/author/paul-ramsburg)

This article presents the findings concerning release agents as described in the previous Ramsburg reference.

Reading, T.J., "The Bughole Problem," *Journal of the American Concrete Institute*, v. 69, no. 3, March 1972, p. 165-171.

This paper is often cited in research on bugholes. It summarizes previous studies and suggests future research. Some conclusions are as follow:

- Bugholes are the most troublesome defect in formed concrete surfaces.
- Current specifications (1971) don't clearly state how many bugholes are acceptable.
- Difficulty in controlling bugholes in construction adds to the problem.
- Research is needed on:
  - Developing a suitable yardstick for rating concrete surfaces.
  - Developing more know-how on how to control bugholes.

Best Practices Guidelines for Self-Consolidating Concrete, Ready Mixed Concrete Association of Ontario, Jan. 2009 p. 12.

In general, SCC mixtures with high slump flow and low viscosity make it easier for entrapped air to be removed and provide the best surface finish.

Entrapped air is most easily removed if the SCC mixture is slowly placed and allowed to move laterally for two meters or more. Pumping from the bottom up generally produces the best finish. Tremie concrete placement from the top of the formwork is the next best option. Troubleshooting tips for bugholes listed in this Guideline follow those in *European Guidelines for Self-Compacting Concrete*, which is also annotated in this bibliography.

Samuelsson, Paul, "Voids in Concrete Surfaces," *ACI Journal, Proceedings*, v. 67, no. 11, Nov. 1970, p. 868-874.

An extensive laboratory study of effects of various factors on the formation of surface voids of concrete structures compacted with internal vibrators. Vibration procedure, concrete slump, lift thickness, form material, release agent, and mix proportions were varied in casting 100 one-story (12 x12-in.) columns. The vibrator used had a diameter of 45 mm, frequency of 10,000 vibrations/min. and an amplitude of 1.2 mm. Vibrator insertions varied from 1 to 8 per lift with durations varying from 5 to 60 sec. Slump varied from 2-3/4 in. to about 8 in. and lift thickness from 6 in. to 47 in. Form facing materials included steel, two types of plywood impregnated faces, rough lumber, dressed lumber, and fiberboard—with and without an oil-tempered surface.

Each column was divided into three segments and each 12-in. test surface on each side of the column was evaluated by the following grading system:

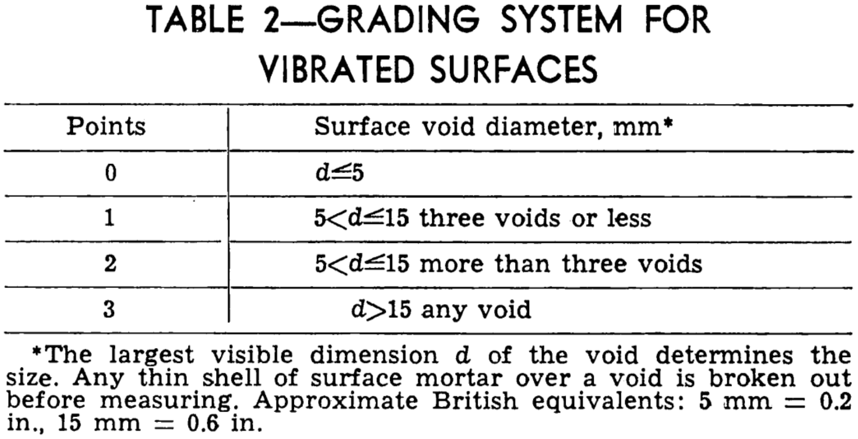


TABLE 2—GRADING SYSTEM FOR VIBRATED SURFACES

Points	Surface void diameter, mm*
0	$d \leq 5$
1	$5 < d \leq 15$ three voids or less
2	$5 < d \leq 15$ more than three voids
3	$d > 15$ any void

*The largest visible dimension d of the void determines the size. Any thin shell of surface mortar over a void is broken out before measuring. Approximate British equivalents: 5 mm = 0.2 in., 15 mm = 0.6 in.

A test surface receiving 0 or 1 points was given a passing grade, so a passing grade for one whole side of a column (three test surfaces) could not exceed 3, and the corresponding passing grade for the whole column was 12. Results for some of the columns are shown in the Table:

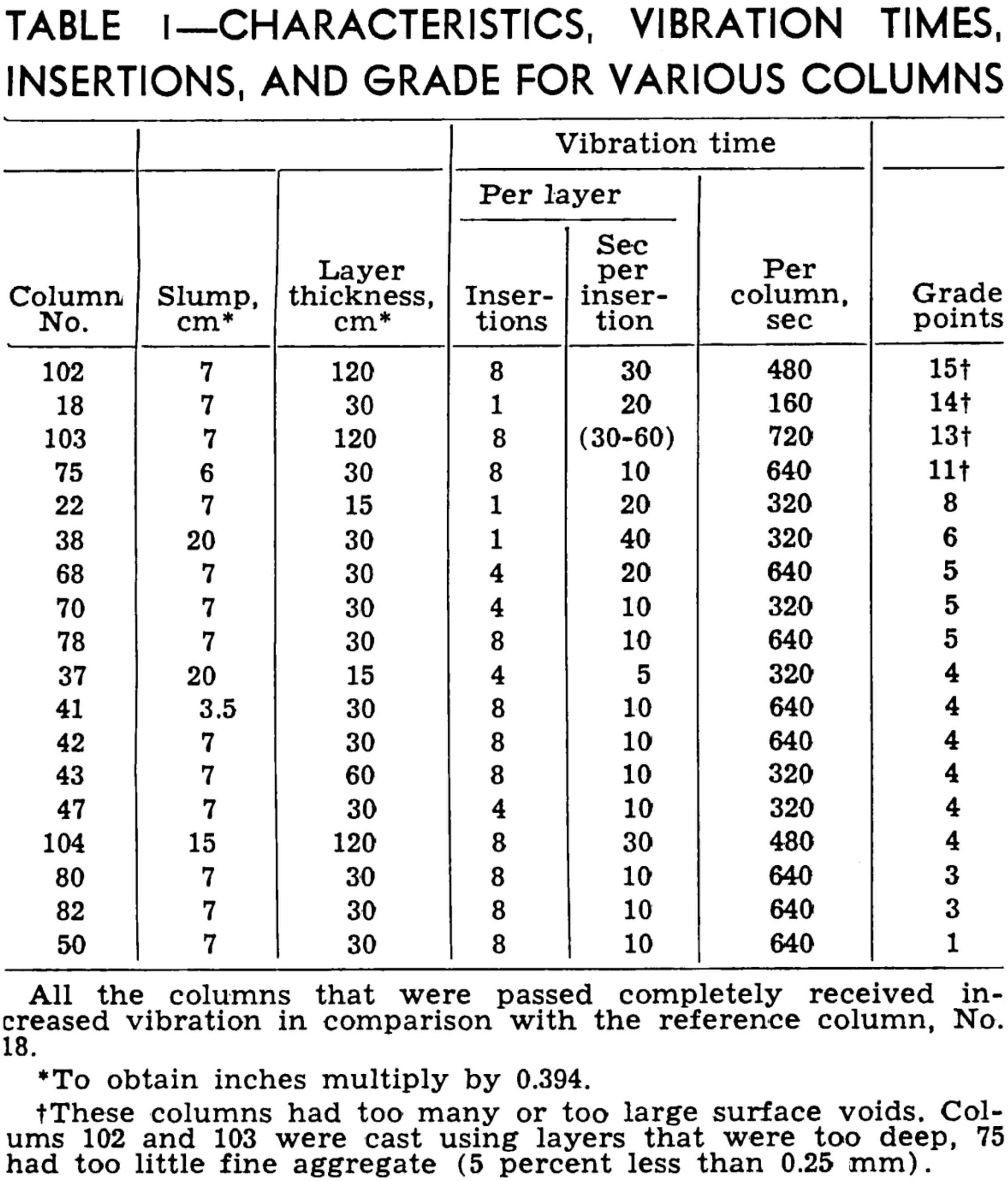


TABLE 1—CHARACTERISTICS, VIBRATION TIMES, INSERTIONS, AND GRADE FOR VARIOUS COLUMNS

			Vibration time			
			Per layer			
Column No.	Slump, cm*	Layer thickness, cm*	Insertions	Sec per insertion	Per column, sec	Grade points
102	7	120	8	30	480	15†
18	7	30	1	20	160	14†
103	7	120	8	(30-60)	720	13†
75	6	30	8	10	640	11†
22	7	15	1	20	320	8
38	20	30	1	40	320	6
68	7	30	4	20	640	5
70	7	30	4	10	320	5
78	7	30	8	10	640	5
37	20	15	4	5	320	4
41	3.5	30	8	10	640	4
42	7	30	8	10	640	4
43	7	60	8	10	320	4
47	7	30	4	10	320	4
104	15	120	8	30	480	4
80	7	30	8	10	640	3
82	7	30	8	10	640	3
50	7	30	8	10	640	1

All the columns that were passed completely received increased vibration in comparison with the reference column, No. 18.

*To obtain inches multiply by 0.394.

†These columns had too many or too large surface voids. Colums 102 and 103 were cast using layers that were too deep, 75 had too little fine aggregate (5 percent less than 0.25 mm).

Column No. 18 was the control column with a cement content of 440 lb/cu yd, mix proportions by weight 1:3.34:3.90, with maximum size aggregate of about 1-1/4 in., 15% of the sand passing a No. 60 sieve, and w/c = 0.71. Release agent was an oil-in-water emulsion. As shown in the table, the control column had a grade of 14, slightly above the 12 set for passing.

Other variables in the testing included form material, type of release agent, cement content, fine aggregate passing the No. 60 sieve, maximum particle size, and air-entraining agents.

Conclusions:

- Vibration procedure had the greatest effect on surface appearance. Vibration should be thorough and sufficient.
- The concrete should be of suitable, not too stiff consistency. [The text states that fluid mixes have fewer voids than plastic mixes, but segregation is more likely and bleeding can result in water-filled pockets (assume this is sand streaking) on the surface.]
- Lifts should be relatively thin.
- More consolidation is needed with impermeable form facings.
- A deficit of fine aggregate passing the No. 60 sieve must be avoided.
- Air-entraining agents can improve the surface appearance.

Reliability of results: Seven columns cast under identical conditions received grades of 6, 10, 12, 14, 17, 21, and 23 (av. About 15 and standard deviation about 6). That was the basis for the following statement:
"Great care must therefore be taken in the interpretation of data from a few comparisons. The wide distribution in the laboratory tests explain why, in actual practice, one succeeds one time and fails another time when the same procedures are used."

Shilstone, James M., "Surface Blemishes in Formed Concrete," *Concrete Construction*, Nov. 1979, p. 719-765.

Discusses many contributors to formed-surface blemishes that aren't mentioned in many articles on bugholes. See the table. Other observations are that mixes with a slump greater than 3-1/2 in. tend to lead to a mottled discoloration when the form facing is hard and a heavy compactive effort is made. Also, fluid mixes, while initially appearing to aid in achieving almost void free surfaces, lead to a high incidence of pinholes in the finished surface. Most of these pinholes are entries to larger voids immediately below the surface; a light abrasive blast would reveal a highly pock-marked substrate.

The author believes consolidation is better when the vibrator is rapidly plunged into the lift below, penetrating for the full length of the head, and then extracted slowly with up-and-down surging movements. Slow insertion of the vibrator head results in entrapment of air below and the surging action during manipulation creates swell forces against the forms, forcing out air bubbles.

"Contractor bids are based on contract documents. If high quality results are to be obtained, it is incumbent on the specifier to so state in his specifications and to provide a reasonable degree of constructability in his contract documents. A weak set of specifications will, for its own lack of direction, assure the production of surface blemishes in great numbers." [underlining added]

CONTRIBUTORS TO SURFACE BLEMISHES IN FORMED CONCRETE

This table is for use in analyzing problems. Many blemishes are the inevitable result of design conditions. When this is recognized the table can be used to analyze projects while still in the design stage to ensure that the design will solve, not create, job problems. Later the details of construction planned by the contractor can be reviewed and approved.

CONSTRUCTION CONDITIONS

- **Restricted form openings**
  - Thin section
  - Shape
- **Battered construction**
- **Interfering construction**
  - Projecting rebars
  - Interference to access
  - Composite structural steel concrete
- **Internal interference**
  - Blockouts
  - Conduits
  - Plumbing
  - Excessive reinforcing steel
  - Steel splices
- **Weather**
  - High temperature
  - Low temperature
  - Precipitation
  - Wind

MIXTURE

- **Sticky**
  - Excessive sand
  - Low sand fineness modulus
  - Excessive minus 50 mesh sand
  - High cement content
  - High air content
  - Excessive pozzolan
  - Particle degradation
- **Harsh**
  - Excessive coarse aggregate
  - High sand fineness modulus
  - Poor grading
  - Poor particle shape
- **Consistency**
  - Too high
  - Too low
- **Temperature**
  - Too high
  - Too low
- **Early stiffening**
  - False set
  - Flash set
  - Excessive mixing
- **Admixture**
  - Improper use
  - Wrong type
  - Wrong dosage

PLACEMENT

- **Bucket**
  - Small mouth
  - Poor configuration
  - Poor discharge control
- **Concrete pump**
  - Requires fluid mix
  - Breakdown
  - Slow delivery
- **Belt conveyor**
  - Segregation
  - Slump loss
  - Mortar loss
- **Hopper/Dropchute**
  - Omitted
  - Too small
  - Insufficient number
  - Unsuitable material
- **Deposit**
  - Spacing
  - Distant from corner*
  - High volume
  - High lift
  - Excessive time interval
  - Equipment breakdown
  - Excessive free fall
  - Rebars interfere

COMPACTION

- **Vibrating equipment**
  - Low frequency
  - Low amplitude
  - Weak power source
  - Too small
  - Too powerful for top
  - Not enough
  - Wrong type
  - Voltage drop
  - Poor maintenance
- **Techniques**
  - Vibration too brief
  - Poor manipulation
  - Spacing too great
  - Not deep enough
  - Head partially immersed
  - Placed too close to form joint
  - Continuity

FORMS

- **Material characteristics**
  - Wrong absorptivity
  - Too rough
  - Adhesion
  - Reaction with the mix
- **Leakage at**
  - Concrete construction joints
  - Form corner joints
  - Form butt joints
  - Tie holes
- **Release agent**
  - Unsuitable type
  - Chemistry of agent
  - Friction with mix
  - Applied too thick
  - Not cured
- **Temperature**
  - Too cold
  - Too hot

OTHER INFLUENCES

- **Curing Discoloration**
  - By environment
  - Metal stain
- **Supervision**
  - Understaffed
  - Unqualified
  - Improper planning
- **Inspection**
  - Understaffed
  - Unqualified
- **Workmen**
  - Uninstructed
  - Unskilled
  - Insufficient numbers
- **Specifications**
  - Inadequate
  - Inappropriate

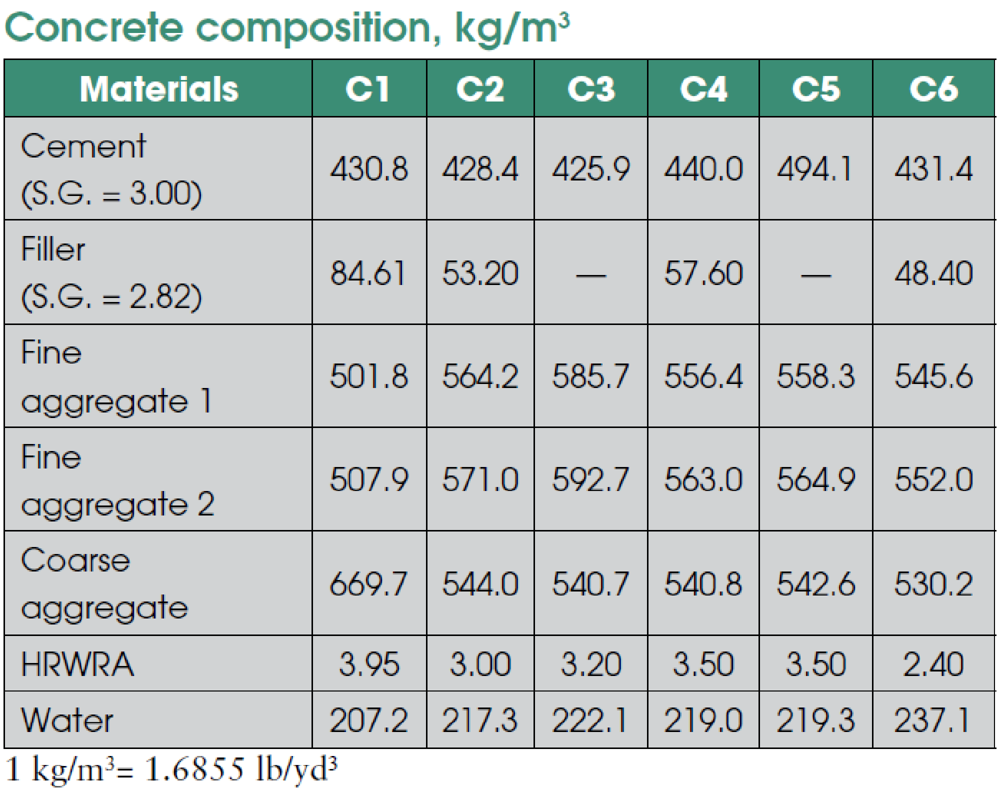
* In walls, beams and girders first deposits should be made at ends and then successively toward center.

Silva, Wilson Ricardo Leal da, Lucena, Diogo Schwerz de, Prudencio Jr, Luiz Roberto, and Stemberk, Petr, “Surface Appearance of Precast Elements Fabricated Using Self-Consolidating Concrete”, *Concrete International*, October 2011.

Describes an experimental program studying the effects on SCC mixes of:

- Mortar content by volume
- Total volume of dusty aggregates
- Ratio of water to total volume of dusty material
- Water-cement ratio
- Dosage of high-range water-reducing admixture

with two different release agents used on laminated plywood forms. Test panels made with six differing concretes (see table) were 1000 x 300 x 80 mm.



Concrete composition, kg/m^3

Materials	C1	C2	C3	C4	C5	C6
Cement (S.G. = 3.00)	430.8	428.4	425.9	440.0	494.1	431.4
Filler (S.G. = 2.82)	84.61	53.20	—	57.60	—	48.40
Fine aggregate 1	501.8	564.2	585.7	556.4	558.3	545.6
Fine aggregate 2	507.9	571.0	592.7	563.0	564.9	552.0
Coarse aggregate	669.7	544.0	540.7	540.8	542.6	530.2
HRWRA	3.95	3.00	3.20	3.50	3.50	2.40
Water	207.2	217.3	222.1	219.0	219.3	237.1

1 kg/m^3= 1.6855 lb/yd^3

Mixture C1 was used for typical production at a precast concrete plant near the authors' laboratory and was the reference (control) mixture for this research. The composition of this mixture was then modified to produce alternate mixtures and study the effects of the modifications on the concrete surface quality based on photographic images of the surfaces.

To simulate precast concrete plant production conditions, the SCC was placed from a height of 1 m at a single point in the mold to allow the concrete to flow from one end of the mold to the other. No vibration was applied.

Concrete surface analysis was based on an image-processing method to create a high-contrast image that highlighted the outlines of bugholes. The projected area of bugholes on the surface was then calculated and expressed as a ratio of void area to the total test area (900 x 250 mm) analyzed. The imaging method was also used to analyze the seven reference photos used for classification in CIB Report No. 24. The results of this are shown in Fig. 5.

The initial modification of proportions from mixtures C1 to C2 resulted in concrete surfaces with a higher area percentage of bugholes. The subsequent SCC mixtures produced surfaces with smaller or nearly equal areas percentages as indicated in Fig. 7 from the article. Note that neither of the two release agents, indicated by A1 and A2, did not have a significant effect on area percentage of bugholes.

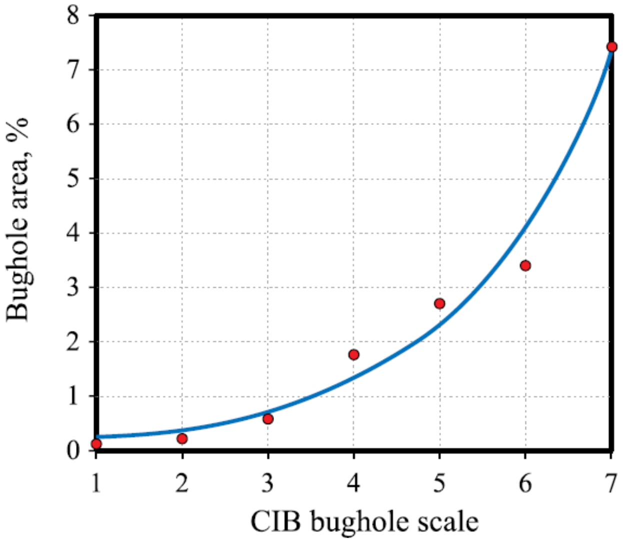


Fig. 5: Bughole area % vs. CIB bughole scale

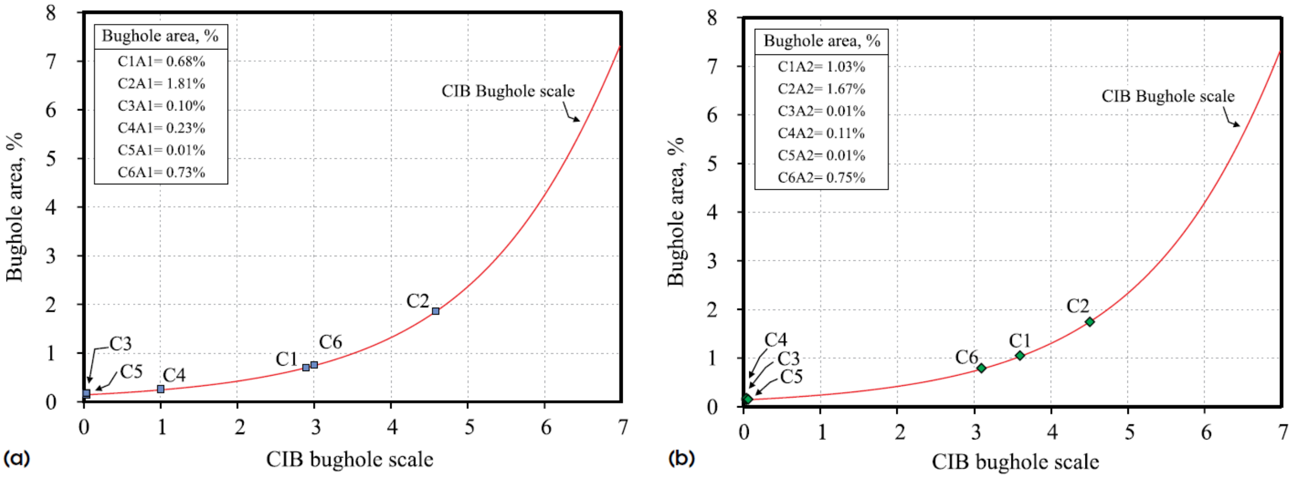


Fig. 7: Classification of concrete surface according to the CIB bughole scale: (a) C1A1; and (b) C1A2

Conclusion: The image analysis method that was used allowed a more objective evaluation of results when compared to the CIB bughole scale.

Silva, Wilson Ricardo Leal da, and Stemberk, Petr, “Expert system applied for classifying self-compacting concrete surface,” *Advances in Engineering Software*, No. 64, 2013, pp. 47-61.

Describes an expert system developed for classifying the surface finish of self-compacting (SCC) precast elements. The paper acknowledges that production of SCC is more difficult than that for conventional concrete because more parameters have to be considered. The expert system is comprised of an image analysis tool and a fuzzy logic-based classification tool. The system takes into account not only surface void ratio, but also the maximum bughole diameter and a bughole size distribution curve. The system output is a classification scale value, C_S, ranging from 1 (defect free) to 5 (patching, changes in concrete mixture, or both are required). Tests were conducted on laboratory-made samples to illustrate the effects of several parameters on C values, production costs, and surface appearance with respect to bugholes.

Smith, John R., “Architectural Concrete: Defects demand discretion,” *Concrete International*, v. 6, no. 1, Jan. 1984, p. 64-66.

> Good architectural concrete requires attention to detail at all levels of design, together with an understanding of its capabilities and limitations. The most professional builder cannot guarantee perfect results since there is no opportunity to eliminate defects as the manufacturers of mass produced products can.
>
> Variations must be viewed with their relationship to the total structure and the consequences of any repair considered. A line of mortar may be undesirable, but a patch could be more pronounced. Variation noticed only under close scrutiny should not be considered for repair.
>
> The examination of detail from the interior should be on the basis of what an occupant of the building would see looking outward through natural openings. Only those variations noted during the initial general examination should be considered for repair for aesthetic reasons.
>
> Excessive voids on the exposed surface are generally not acceptable in quality architectural concrete.
>
> The structural engineer should consider the potential for steel congestion, especially at column to beam connections. While it may be possible to get all of the reinforcement within the formwork, concrete placement may be difficult, if not impossible. Modification by the structural engineer of the reinforcing steel details, or use of modified architectural concrete mixes may be necessary, with careful consideration given as to the effect on the end appearance.

Spahr, Rolf and Johnston, David, “The new “Guide to Formed Concrete Surfaces,” *Concrete International*, June 2014, pp. 31-32.

States that ACI 347.3R-13 can be used by:

- Specifiers—for the development of contract documents that define the required quality levels, methods, and procedures of evaluation for concrete surfaces;
- Owners—for assistance in visualizing their projects and developing realistic expectations; and
- Contractors—for guidance in the selection of facing materials, concrete mixtures, release agents, and construction methods as well as in the development of price quotations commensurate to the specified surface finishes.

A section on surface finish limitations describes surface characteristics considered unacceptable or objectionable, and it distinguishes those that are preventable. However, recognizing that some surface characteristics are difficult to control and can be considered inherent to concrete construction, the guide also helps make all parties aware of what is realistically achievable in as-cast concrete.

Note: Section 5.3 in ACI 347.3-13 includes the following: When specifications require a concrete surface quality that is greater than the characteristics described in Table 3.1a, the specifier should be aware of what is realistically achievable in as-cast concrete. This then assumes that the requirements for all for all four formed surface categories are realistically achievable. ACI 347.3R-13 doesn’t provide enough data to validate that assumption.

Specifications for Structural Concrete (ACI 301-16) American Concrete Institute, 2016, p. 25.

Includes the following measurable and objective requirements for three different surface finishes:

Surface finish-1.0 (SF-1.0):
(a) No formwork facing material is specified
(b) Patch voids larger than 1-1/2 in. wide or 1/2 in. deep
(c) Remove projections larger than 1 in.
(d) Tie holes need not be patched
(e) Surface tolerance Class D as specified in ACI 117
(f) Mockup not required

Surface finish-2.0 (SF-2.0):
(a) Patch voids larger than 3/4 in. wide or 1/2 in. deep
(b) Remove projections larger than 1/4 in.
(c) Patch tie holes
(d) Surface tolerance Class B as specified in ACI 117
(e) Unless otherwise specified, provide mockup of concrete surface appearance and texture

Surface finish-3.0 (SF-3.0):
(a) Patch voids larger than 3/4 in. wide or 1/2 in. deep
(b) Remove projections larger than 1/8 in.
(c) Patch tie holes
(d) Surface tolerance Class A as specified in ACI 117
(e) Provide mockup of concrete surface appearance and texture

Does not reference bughole frequency (number of bugholes/unit area).

Stamenkovic, H., "Surface Voids Can Be Controlled," *Concrete Construction*, v. 18, no. 12, Dec. 1973, p. 597-600.

This article suggests means for controlling bugholes in concrete surfaces. Suggestions include:

- Using both internal and external vibration combined with hammering and revibration.
- Using fine sand with a high surface area. Larger amounts of sand are not as effective as using finer sand (particles passing the No. 50, 100, and 200 sieves).
- Using smaller coarse aggregates, with particles more nearly spherical.
- Avoiding crushed aggregate.
- Using finely ground cement.
- Mixing concrete longer than normal.

The article states that water voids on the formed concrete surface are nearly spherical in shape and are typical of concrete with a high w/c. Sizes of these voids range from about 1/8 in. to microscopic dimensions. The prime characteristic of air voids is their irregular shape. "Almost never are they purely spherical…" size of air voids vary from about ½ in. to microscopic dimensions.

Szcesy, Richard, and Mohler, Nathaniel, "Self-Consolidating Concrete," IS546, Portland Cement Association, Skokie, IL, 2015, p.12-13.

Properties of SCC that can result in bugholes include:

- Poor filling ability (Unconfined flowability ASTM C1611)
- Poor passing ability (ASTM C1621; also, U-box or L-box test)
- High viscosity or yield stress (V-funnel test)
- Low slump flow or rapid slump flow loss. (ASTM C1611)

Thompson, M.S., “Blowholes in concrete surfaces,” *Concrete* (London), v. 3, no. 2, Feb. 1969, p. 64-66. (Also *Concrete Construction*, 1970)

An early synopsis of results of an investigation into the occurrence of blowholes and the methods of reducing or eliminating them. A standard of reference that can form a basis for specifications is recommended. Ideally, the standard would be a series of full-size sections of the structure under discussion. If this is impractical, the author suggests that smaller panels may be adequate, and failing this, one-foot-square full-sized photos may be used. A set of ten such photos is included in small scale, and the author states that the use of such photos has been adopted in preference to a number of more sophisticated methods based on the measurement of diameters and areas of holes [See Houston, B.J.]. The author also claims that using the photos is much simpler and is generally equally or more satisfactory than other methods.

“Blowholes are endemic in concrete, and a wise architect will avoid specifying finishes that are free of blowholes, unless he allows the holes to be filled in after the forms are removed. Often, the formation of a moderate number of holes is unobjectionable, and the architect may even welcome their formation as being characteristic of the material with which he is working. Often, too, they are far less noticeable than the so-called ‘making good’ [repair] which disfigures much exposed concrete.”

“Several factors influence the formation of blowholes, but by far the most outstanding appears to be the way in which the concrete is placed and compacted.”

Fig. 2 shows a “situation which must occur frequently”--a vibrator immersed in a pile of concrete, having been placed in that position before or after the pile was deposited. If the vibrator is left immersed until the concrete reaches the position of the broken line, and is then withdrawn vertically and relatively quickly, Thompson believed that in flowing from left to right the concrete at A would expel most of the entrapped air and exhibit few blowholes. At B, however, where there was less lateral flow, air rising near the vibrator would accumulate and be trapped, or perhaps air would be drawn in near the top, creating more blowholes at B. He suggested that moving the vibrator over that area at a small angle to the horizontal would reduce the number of blowholes.

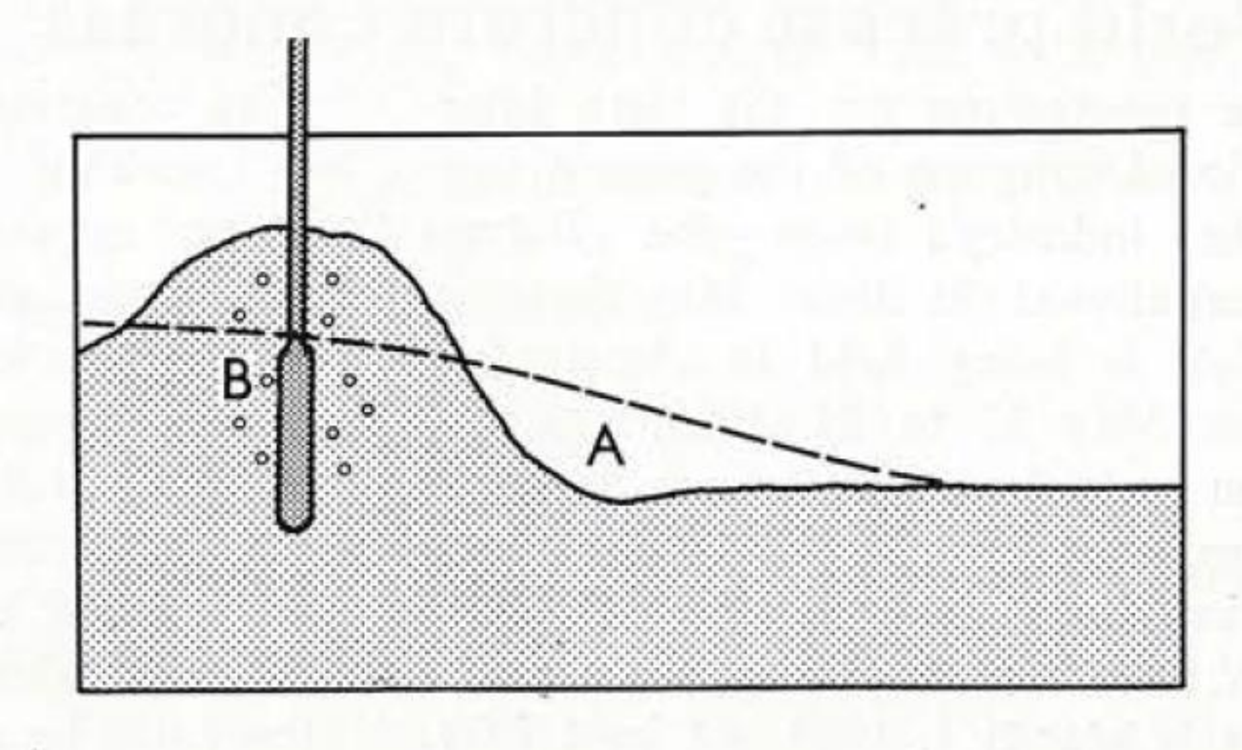


Fig. 2 Diagram shows effect of placing heap of concrete in wall before and after vibrating. Blowholes will appear at B but not at A.

Tsukinaga, Y.; Shoya, M.; Sugawara, R.; Nonome, H., "Improvement in Concrete Performance and Durability Using Permeable Sheet," *Advances in Concrete Technology*, SP-154, American Concrete Institute, 1995, p. 279-99.

> Describes a laboratory study on the effects of permeable form liners on concrete surface properties including bugholes. Concrete with a target w/c of 0.65 and slump of 80 mm was placed in the Series 1 form shown in Fig. 2. Form faces were covered with permeable sheets or left bare. No details are given as to the uncovered form face, release agent used (if any), or compaction methods used.
>
> Outlines of bugholes on the upper, middle, and lower concrete surfaces shown in Fig. 2 were traced on 100x200 mm transparent sheets. The area of bugholes was calculated and expressed as a percentage of the area (SVR) of the transparent sheets. As shown in Fig. 5, the SVR ranged from about 0.3% at the bottom, 3.4% on the slanted part of the form, and 0.5% at the top of the form.

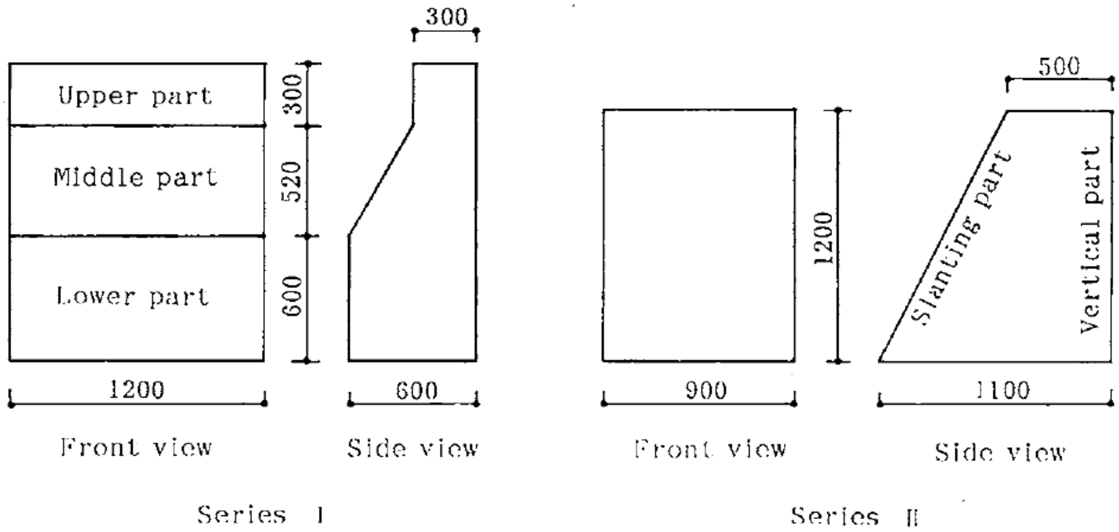


Fig. 2—Outline of model concrete used in test

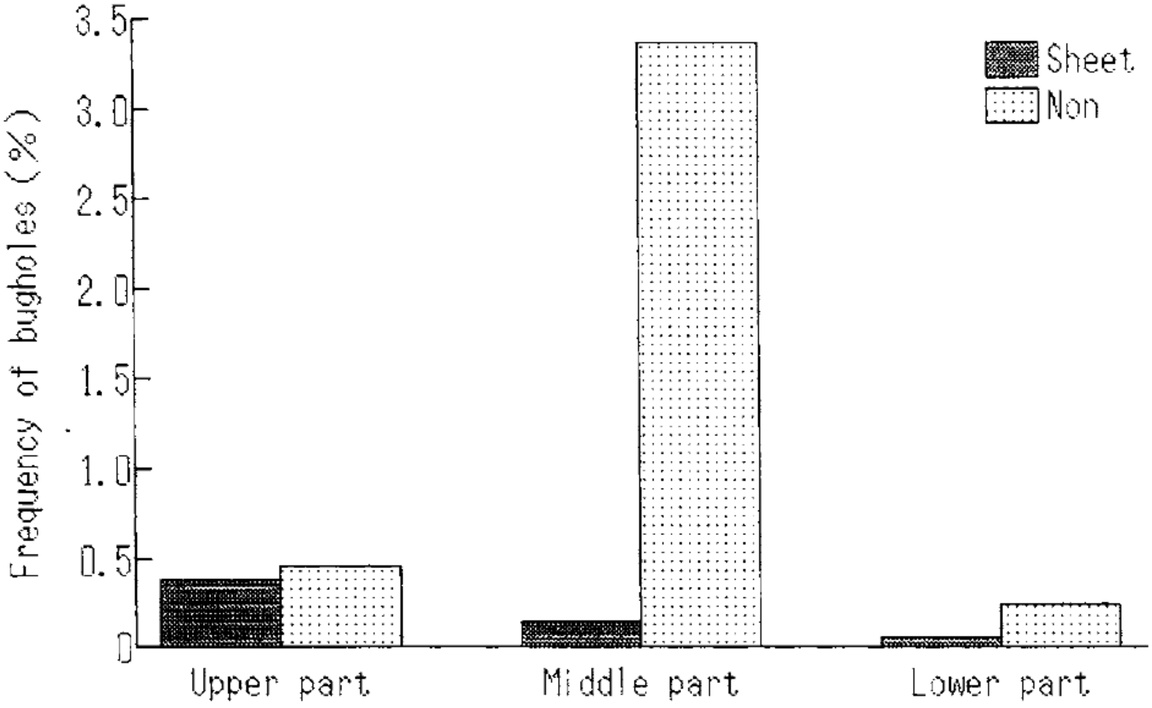


Fig. 5—Frequency of bugholes

Vikan, Hedda, “Quality of Concrete Surfaces – State of the Art”, Report No. SBF BK A07013, SINTEF Building and Infrastructure, 2007 36 pages.

A summary of parameters affecting the quality and aesthetics of formed and finished concrete surfaces. Includes a summary of *Deutscher Beton-und Bautechnik-Verein (DBV) e.V. 2004*, the document containing classification tables that are the basis for the classification system used in ACI 347.3R-13. Four concrete classes (SB-1 through SB-4) have differing requirements for:

o texture (demand classes T1-T3)
o porosity (demand classes P1-P4)
o steadiness of shade (demand classes FT1-FT3)
o surface evenness (demand classes E1-E3)
o quality of formwork skin (demand classes SHK1-SHK3)
o quality of formwork joints (demand classes AF1-AF4)

The four classes are described in Tables 1, 2, and 3 as follow:

Table 1: Concrete classes according to DBV 2004

Classes of architectural concrete		Examples
Concrete with insignificant demands	SB1	Basement walls, areas with industrial use
Concrete with normal demands	SB2	Stairs, supporting walls
Concrete with high demands	SB3	Facades
Concrete with especially high demands	SB4	Representative components

Table 2: Classes of architectural concrete given by DBV in combination with the demands (Litzner and Goldammer 2005).

Concrete class	Texture	Porosity		Shade		Evenness	Trial sample	Formwork skin	Formwork Joints
		A$^{1)}$	Na$^{2)}$	A$^{1)}$	Na$^{2)}$				
SB1	T1	P1		FT1		E1	Optional	SHK1	AF1
SB2	T2	P2	P1	FT2			Recommended	SHK2	AF2
SB3		P3	P2			E2	Highly Recommended		AF3
SB4	T3	P4	P3	FT2	FT3	E3	Imperative	SHK3	AF4

A$^{1)}$ = Absorbing formwork, Na$^{2)}$ = Not absorbing formwork

Table 3: Definition of porosity classes given by DBV (Litzner and Goldammer 2005).

Porosity class	P1	P2	P3	P4
Maximum pore units in mm^{2*}	Ca. 3000	Ca. 2250	Ca. 1500	Ca. 750*

*Pore units in mm^{2} of pores with diameter within the limits of 2 mm and 15 mm. 750 mm^{2} corresponds to 0.30 % of the test surface (500x500 mm)

Excerpts:

Blowholes result from the migration of entrapped air (and to a lesser extent water) to the fresh concrete-form interface during placement and consolidation. During consolidation, the densification and subsequent volume shrinkage of the fresh concrete forces entrapped air and excess water out of the cement matrix. The water will then tend to migrate upward due to its relatively low density and become bleed water. The air bubbles, however, seek the nearest route to reach pressure equilibrium. For a vertical form, the closest distance for the air bubbles' migration is to the interior form surface. Blowholes are, however, found more frequently in the upper portion of the concrete structure or at angled form surfaces as a result of additive accumulation of escaping air voids along the height of the structure **[See also Linder 1992**].

Mix design can be a significant contributor to blowhole formation. A sticky or stiff mixture that does not respond to consolidation can for instance be directly linked to increased surface void formation. Workable, flowing mixtures are easier to place and consolidate and reduce therefore the risk of blowhole formation. Concrete mixes that are richer in cement tend to show fewer blowholes than leaner mixes of the same workability. The effect of the cement content on a mix made with a well-graded aggregate appears, however, to be negligible (Thomson 1969). Silica fume and other pozzolanas such as granulated blastfurnace slag and fly ash have been shown to improve the concrete surface qualities as it reduces bleedwater in the concrete. As a result, voids caused by trapped bleed water are absent (Neville 1995).

Improper vibration is perhaps the most influential cause of blowholes. Consolidation, usually through vibration, sets the air and water bubbles into motion. A proper amount of vibration sends both entrapped air and excess water to the free surface of the concrete – either vertically winding through the matrix or laterally in a direct route to the form wall. When impermeable forms are used, more vibration is necessary to move the air voids to the free surface of the concrete.

The fluidity of SCC and the elimination of vibration result in improved surface quality of the concrete. SCC has normally less bleeding tendency than vibrated concrete. It has a uniform quality, the binder phase is denser and there are fewer weakness zones between aggregates and paste.

SCC surfaces have been found to be smoother compared to normal vibrated concrete. Pour lines, bugholes, honeycombs, gravel grooves [sand streaks?] and other surface imperfections are also largely reduced (Johansen 1999, Gaimster and Foord 2000). SCC renders, moreover, improved microstructural features leading to potential improvements of strength, durability and surface quality (RILEM 2006).

An improved surface appearance is generally obtained with slump flow values greater than 610 mm with controlled rheological properties and minimal to no bleeding characteristics (ACI 237R-07). It is important to control the workability of the concrete over time since workability loss causes poor filling ability and thus surface defects (Gram 2004). Surface defects might also occur due to the retarding effect of the superplasticizer and/or low casting temperatures. During the prolonged setting time, the concrete may segregate or bleed, allowing water to be transported to the mould surface, where it may produce blowholes or stream upwards along the mould. Other contributing factors could be the interaction with the form releasing agent (type and thickness) applied to the moulds.

Whenever possible, SCC should be deposited continuously and in layers of such thickness that no fresh SCC is placed on concrete that has hardened enough to cause a seam or plane of weakness. Some SCC have thixotropic characteristics, and may then be placed onto previously placed SCC that has gelled but not yet achieved initial set. ACI (237R-07) recommends in this case to use an internal or external vibrator for a 2- to 3-second duration to avoid pour lines in the piece. RILEM (2006) and Trägårdh (1999), however, advise against vibration of SCC and claim that any external vibration to remedy honeycombing or bugholes will do more damage than good. They have found that vibration can cause bleeding, sand-streaking, accumulation of pores and severe aggregate segregation within the unit.

SCC mixes are characterised by a moderate to higher amount of fines in the formulation, including various combinations of powders such as Portland cement, limestone filler, silica fume, fly-ash or ground granulated blast furnace slag. Thus, there might be very little or no bleeding and the concrete may thus be more sensitive to plastic shrinkage cracking. The tendency of plastic shrinkage increases, however, with the increase in the volume of fines. This situation is sometimes more complicated if the setting time is delayed because of the admixture effect. Curing to counteract longer term shrinkage is to be handled like what is done for vibrated concrete. It should be observed that due to a lower permeability of SCC, the drying rate and thus also the shrinkage rate might be slower (RILEM 2006).

Appendix D

Testing Program Details

Middle Tennessee State University (MTSU) Wall

In late April of 2015, Concrete Industry Management (CIM) student researchers at MTSU formed and placed a concrete footing, then set prefabricated form panels for a U-shaped wall 8-in.-wide and 4-ft tall (Photo 1). This was part of a closing exercise in a Formwork for Concrete class and these students were aided by members of a Senior Concrete Research class. They used rented forms faced with overlaid plywood. To simulate a typical basement wall pour, no special care was taken to use only forms with facing in good condition. A chemically reactive form release agent was applied before setting the forms. (Photos 2-3).

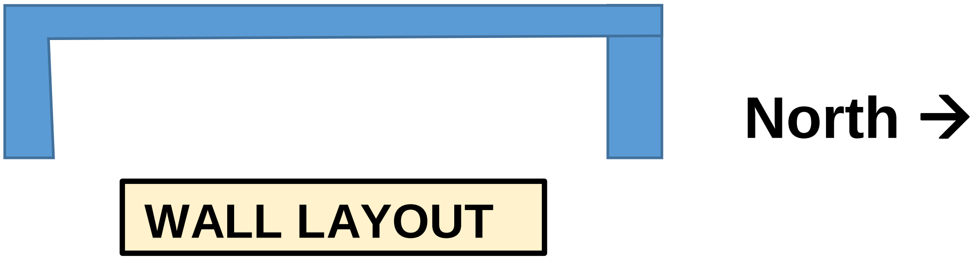


Photo 1. Layout for MTSU wall. Numbers refer to positions of first four 2x2-ft sample locations.

Photo 2. N and W outside wall forms **Photo 3. W outside wall forms**

Setting wall forms with form release applied

Bulkheads were placed in the completed forms to divide the wall into four sections, with the intent to vary vibration methods. However, it became apparent early in the placement that varying vibration methods would take too much time. All sections of the wall were vibrated until the mass subsided and the rate at which bubbles rose had slowed. The concrete was a 5-½-in. slump proprietary wall mix with a target air content of 5.0% (Photo 4).

Photo 4. The 5½-in. slump proprietary wall mix had good cohesion

Student researchers placed it from a front-discharge truck in two-two-ft-thick lifts and consolidated the concrete with 2-in.-dia. internal vibrators (Photos 5-6).

Photo 5. Concrete placed in the forms from a front-discharge truck.

Photo 6. Vibration with a 2-in.-diameter internal vibrator

Forms were stripped the following day. Photos were taken to record the initial surface condition followed by later photos to record color changes with time (Photos 7 and 8).

Photo 7 Outside face, north wall on day forms were stripped
.

Photo 8 Outside face, north wall 6 weeks after forms were stripped. Note that much but not all of the discoloration is less apparent.

New Jersey Institute of Technology (NJIT) Wall

In July 2016 CIM student researchers and Dr. Mohamed Mahgoub, their advisor from NJIT, met with the Project Management Team of Ruttura and Sons Construction, the contractor for a structure being built in New York City. After being briefed by Ruttura's Safety Director, Janet Stanton, the students measured SVR on six randomly chosen 2x2-ft samples on a 100-ft long, 15-in.-thick cast-in-place exposed wall (Photo 9).

Photo 9. CIM student researchers mark off a randomly chosen 2x2-ft sample before measuring SVR for the sample surface.

Forms for the wall were faced with birch plywood that was covered with plastic sheets sprayed with Formkote OTC, a chemically active form release agent. A concrete pump was used to place the 4000-psi, air-entrained concrete with a target slump of 4 ± 1 in. and air content of 6% ± 1½%. Admixtures included a vinsol resin air-entraining admixture and a retarding-water reducing admixture (ASTM Type D). Mixture proportions were as follows;

Material	**Batch quantities(lb/cu yd)**
Cement Type I/II	489
Slag cement	122
Fine aggregate	1230
Coarse aggregate (1-in. NMS)	1900
Water	269

The wall was placed monolithically, with workers using 2-½-in. diameter internal vibrators inserted every 2 feet along the wall for 5 to 10 seconds.