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Ward R. Malisch Concrete
Construction Symposium

SP-338

Editors:
Bruce A. Suprenant and Oscar R. Antommattei



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Ward R. Malisch
Concrete Construction Symposium

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Editors:
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PREFACE

Ward R. Malisch Concrete Construction Symposium

Ward R. Malisch spent most of his 50-year career addressing issues related to concrete construction, specifically to problems that concrete contractors deal with daily. His civil engineering training began at the University of Illinois at Urbana-Champaign where he received his BS, MS, and PhD in 1961, 1963, and 1966, respectively. During his time at Illinois he also carried out research on concrete durability and taught courses on plain concrete. Following that, he taught courses in concrete construction at the University of Missouri-Rolla (now Missouri University of Science and Technology) where he received several awards for outstanding teaching. During his time there he took a leave of absence to work in quality control for the prime contractor building Missouri's first nuclear power plant. This experience spurred his interest in how specification requirements and tolerances affected contractors' abilities to build both simple and complex structures.

Malisch was able to reach the construction industry more directly when he joined the staff of the World of Concrete seminar program and later became editor of Concrete Construction magazine. He was then able to teach at a national level by further developing a seminar program and editorial content that featured how-to-do-it information on concrete technology, with an emphasis on contractor-related topics. During his tenure with the magazine, he began answering questions on a telephone hotline service offered by the American Society of Concrete Contractors (ASCC), and gave advice on problems related to unrealistic concrete tolerances, inadequate knowledge about plastic concrete properties, ambiguous specifications, and a wide range of other construction-related topics.

In subsequent years, Malisch served as director of engineering and later as senior managing director at the American Concrete Institute. There, while supervising the engineering, marketing, and education departments, and serving as publisher of Concrete International magazine, he also interacted with other concrete-related organizations, serving on the Research, Engineering, and Standards Committee of the National Ready Mixed Concrete Association and on the ASCC Board of Directors. Along with the ACI Strategic Development Council, ASCC, and Construction Technology Laboratories, he helped to organize an Inter-Industry Working Group on Concrete Floor Issues that brought together leaders from several construction and flooring industry groups. One outcome of this group's activity was publication of ACI 302.2R-06, "Guide for Concrete Slabs that Receive Moisture-Sensitive Flooring Materials."

Upon retirement from ACI in 2008, he was named technical director of ASCC. He was active again in forming an Inter-Industry Working Group on Reducing the Cost of Tolerance Compatibility Problems along with eight other co-sponsoring groups. He later served as principal investigator on two construction related research projects dealing with contractor-related problems.

Dr. Malisch's awards include:

- 1986— Elected Fellow of the American Concrete Institute
- 2004— Arthur Y. Moy Award, ACI Greater Michigan Chapter
- 2006— Silver Hard Hat Award, highest award given by the Construction Writers Association

- 2008— Richard D. Gaynor Award, Highest technical award given by the National Ready-Mixed Concrete Association
- 2009—One of Concrete Construction magazine's Most Influential People
- 2010— Arthur R. Anderson Medal, ACI, given for outstanding contributions to the advancement of knowledge of concrete as a construction material
- 2011— ACI Construction Award, given to the author of any paper of outstanding merit on concrete construction practice
- 2011— ASCC Lifetime Achievement Award, ASCC's highest honor, acknowledging recipients for their body of work within the industry and their service to ASCC
- 2013— ACI Honorary member, given to a person of eminence in the field of the Institute's interest or one who has performed extraordinary meritorious service to the Institute
- 2019—Roger H. Corbetta Concrete Construction Award, ACI, given to an individual that has made significant contributions to progress in methods of concrete construction.

For his dedication to the concrete construction industry, this Special Publication is a tribute to his work and is sponsored by the ACI Construction Liaison Committee. Sixteen presentations, distributed in four sessions named "Ward R. Malisch Concrete Construction Symposium," were given at the 2017 ACI Fall Convention in Anaheim, CA. The quality of the presentations was highlighted by the participation of four former presidents of ACI: David Darwin, Terry Holland, Ken Hover and Mike Schneider.

The nine manuscripts presented in this Special Publication are significant in that each paper represents authors that have been previously published in ACI. Thanks are extended to the many ACI members who reviewed the manuscripts and provided helpful technical and editorial comments which enhanced the authors' papers.

This Special Publication is but one small token of appreciation and gratitude to the more than 50-year service of Ward R. Malisch to concrete construction. He has been a source of inspiration to many as well as an example of honesty, integrity, and dedication. He has built the foundation for others to build upon in serving the concrete construction industry.

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Can Bugholes Be Evaluated Objectively on As-Cast Concrete Surfaces?

Ward R. Malisch, PhD, P.E. Hon. Member ACI and Heather Brown, PhD, FACI

Synopsis: Bugholes on as-cast surfaces are an aesthetic issue, not a performance issue related to strength, durability, or serviceability. Because they are an aesthetic issue, attempts to evaluate bugholes objectively, with measurements, are not useful. Measuring bugholes using an evenly divided scale or other instrument can reveal their number, individual area, and total area as a percentage of a sample area. But there is no scale or instrument for aesthetic judgments. Thus, matching a mock-up surface with the as-cast surface, although subjective, is a better method for acceptance of surface appearance.

Keywords: aesthetics; bugholes; forms; surfaces; performance; rating systems

Ward Malisch is the Concrete Construction Specialist for the American Society of Concrete Contractors. He has taught civil engineering materials courses at several universities, worked in quality control for a major contractor, and previously served as ACI's senior managing director. He is a current member of ACI Committee 301 on specifications and an Honorary Member of ACI.

Heather Brown is a professor and director of the School of Concrete and Construction Management at Middle Tennessee State University. Her technical experience includes five years of material testing and research for the Tennessee Department of Transportation. An ACI Fellow, she is a current member of SCI Committee 522 on pervious concrete and of the ACI Board of Direction.

INTRODUCTION AND BACKGROUND

In 1972 Reading¹ stated that bugholes (also called surface air voids) in as-cast concrete surfaces were of concern to most owners and architects—a statement that is still true today. He 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. In summary, he said: “We need a yardstick for rating concrete surfaces with respect to bugholes, and more know-how on how they can better be controlled.”

SUBJECTIVE RATING SYSTEMS

One such yardstick is a subjective rating system. The systems compare an as-cast concrete surface with standard photographs of surfaces exhibiting bugholes of varying size, number, and concentration. The number of standard photographs used can range from 0 to 7 increments, with the larger numbers indicating a higher incidence of bugholes. A specifier could thus require a lower number for architectural concrete and higher numbers for less important structures.^{2,3,4} One system of this type appears to still be in use in Australia.⁵ Subjective rating systems can be affected by personal opinions, interpretations, points of view, emotions, and judgment. This is a major detriment of such systems' bias.

OBJECTIVE RATING SYSTEMS

Objective information is fact-based, measurable, and observable. Several objective rating systems for bugholes have been proposed.^{6,7,8} Some of the most recent are included in ACI 301-16⁹ and in ACI 347.3R-13.¹⁰ The former is a specification that defines three surface finishes (SF-1.0 through SF-3.0), based upon several measurements that include patching surface voids that exceed specified dimensions. The lowest quality surface—SF-1.0—requires patching of voids larger than 1½ in. wide or ½ in. deep, presumably including both bugholes and honeycomb as voids. SF-2.0 is the default finish, and SF-3.0 is the highest quality finish, with both requiring patching voids larger than ¾ in. wide and ½-in. deep. A mock-up is optional unless otherwise specified for an SF-2.0 and is mandatory for an SF-3.0 finish. There is no limit on the number of bugholes smaller than ¾ in. wide and ½-in. deep, but differences in appearance between the mock-up and as-cast surfaces would reflect differences in the number of bugholes. ACI 301-16 is a mostly objective specification for bugholes, although matching an as-cast surface with a mock-up surface is clearly subjective.

ACI 347.3R-13 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). This Guide is claimed to provide objective methods for evaluation of formed surface characteristics such as porosity,¹¹ which is measured and expressed as a surface void ratio (SVR), defined as the total area of bugholes in a 2x2-ft (610 x 610 mm) square sample expressed as a percentage of the sample area. There are four SVR categories ranging from SVR1 (the lowest quality surface) to SVR4 (the highest quality surface). Recommended SVRs for the four categories are shown in Table 1, along with a footnote and additional note.

Table 1 Surface void ratios recommended (SVR) for as-cast formed surfaces

SVR1	SVR2	SVR3	SVR4
Max. area = 6.9 in. ² (4452 mm ²); <i>Dmax</i> = 3/4 in. (19 mm)	Max. area = 5.8 in. ² (3742 mm ²); <i>Dmax</i> = 5/8 in. (16 mm)	Max. area = 3.5 in. ² (2258 mm ²); <i>Dmax</i> = 3/8 in. (9.5 mm)	Max. area = 1.7 in. ² (1095 mm ²); <i>Dmax</i> = 1/4 in. (6 mm)
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.

*Void area is the summation of the areas of all voids within the sample space of 24 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 mock-up 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 mock-up.

A CLOSER LOOK AT ACI 347.3R-13

Section 3.2 of ACI 347.3R-13 states that: “The surface void ratio is only required to be determined if the entire impression of the surface does not meet the contract expectation.” But the “entire impression” is a subjective judgment that can overrule the objectively measured SVR.

Section 3.2 also describes a procedure for measuring SVR on a single sample, with no indication of how the sample is chosen. A rectangle is superimposed over each void in the sample space such that about as much void area falls outside the rectangle as non-void area falls inside. The area of each rectangle is measured, then the areas are summed and expressed as a percentage of the sample area. Another option is measuring each void area with a circle or square template superimposed over the bughole in the same manner as the rectangle.

The final report of a research project that examined and evaluated ACI 347.3R-13¹² cited two 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 were not reported and no data were presented regarding variability of results using the method.

Sampling is critical, and the “sample-of-one” approach recommended in ACI 347.3R-13 was shown in the research report to lead to either rejection or acceptance of the same wall, depending on sample location. Thus, the use of more than one sample was studied, with several different measuring methods. Students in Concrete Industry Management programs at three universities made measurements on different walls. Further, three independent testing laboratories made measurements on each of three different walls constructed in three different states by different contractors. Shown in Fig. 1 is a shear wall with an as-cast finish in the garage portion of a high-rise condominium. Nine randomly chosen, non-overlapping sample locations were marked. Fig. 2 shows results of SVR measurements by a testing laboratory manager and two technicians on all nine samples. They used a square template, which they found to be a faster method for void measurement. Note that the average SVR was 0.4%, which would place the wall in the SVR3 category. But note also that individual results for the three measurements of each sample, due to differences in reproducibility, could have placed the wall in any of the four SVR categories.

Thus, the average of several samples is needed to categorize a wall, and reproducibility of the proposed void measurement methods is suspect.

Photographic methods are being developed using software programs to precisely and accurately measure the surface void ratio of samples and relate them to photos of the same surface.¹³ Some researchers also suggest two “visual impact ratios” with *ratio one* being the same as the SVR, and *ratio two* obtained by dividing the SVR by the total number of voids. This second ratio is an indicator of whether or not the number of bugholes visible from a distance is significant. A small *ratio two* indicates that the number of bugholes visible from a distance is insignificant. Thus, they state that the smaller these two ratios are, the higher the quality of the surface.¹⁴ Eventually, it may be possible to rapidly and accurately measure the two ratios for an entire wall. But would the results of such measurements give us an objective measurement of the wall’s aesthetic quality?

PERFORMANCE AS OPPOSED TO AESTHETICS

Bugholes are listed as defects in AIA MasterSpec®¹⁵ and as “negative surface effects” in ACI 309.2R-15.¹⁶ These two documents can be applied to any structural concrete surfaces exposed to view—not just architectural concrete surfaces. But the term “defect,” when applied to structural concrete usually refers to performance issues related to strength, durability, or serviceability. Performance of vertical as-cast surfaces that receive no coatings or other surface treatments is rarely, if at all, affected by bugholes. So this is not a performance issue.

Thus, considerations of aesthetic appeal or pleasing appearance seem to be the major reason for attempting to limit the size and number of bugholes on formed surfaces.¹⁷ But how does one quantify aesthetics? What quantifiable features of bugholes make a surface beautiful or ugly?

IS QUANTIFICATION OF AESTHETICS USEFUL?

Any concept can be quantified, but such attempts at quantification are not necessarily useful. Many methods for quantifying art or aesthetics have been proposed, all with flaws that make them imperfect. A good discussion of the reasons is presented by Naukkarinen¹⁸ in his paper “Why Beauty Still Cannot be Measured.” He states that aesthetic judgments based on the same measurements can vary to a great extent if the evaluator is changed. Further, in measuring, one normally uses an evenly divided and hierarchical scale. The numbers indicate if something is bigger than something else and by how much. But there is no scale or instrument for aesthetic judgments.

As an example related to bugholes, measurements reveal their number, individual area, and total area as a percentage of a sample area, expressed as the SVR. But the four SVR categories in ACI 347.3R-13 suggest that there is an aesthetic difference among the categories based on SVR, thus implying for a given range in SVR, the aesthetic qualities are similar. Consider the three drawings in Fig. 3. They are drawn to scale and represent concrete surfaces with bugholes of three sizes and with identical surface void ratios. The SVR for each is just under 1.0%, the borderline between an SVR2 and an SVR3. The only difference in the three drawings is the concentration or areal distribution of the bugholes. Which of the three is most pleasing to the eye? The SVR measurements are of no help in making such a decision, because qualities such as symmetry, proportion, balance, and other such factors vary even though the SVR remains constant. It is also likely that differing owners or architects would have differing opinions as to the acceptability of any of the three bughole distributions.

Finally, in Fig. 4, examine the two photographs from the interior of the Herbert F. Johnson Museum of Art on the Cornell University campus. This monumental structure won an AIA New York honor award in spite of the rather large bugholes seen in photos of the board-finished surface for a stairway. These bugholes were cited specifically by a panel of architects as an aesthetic feature of the museum’s interior. The surface was described as: “richly textured” with a “porous surface that resembles a sea-tossed shell.”

HOW TO BEST EVALUATE BUGHOLES

If appearance of vertical concrete surfaces is not of concern, there is little need for detailed restrictions on bughole size, number, or concentration. Using the ACI 301-16 default surface finish of SF-2.0 should be satisfactory for

most surfaces. An exception is for surfaces to be painted or coated, which may require a grout-cleaned rubbed finish as described in Section 5.3.3.4(a) of ACI 301-16. This makes paint or coating failures less likely.

Based on the information in this paper, do not evaluate bugholes as a separate aspect of formed surface appearance for architectural concrete surfaces. Instead, construct a mock-up and compare the general appearance of the final structure with the general visual appearance of the mock-up as is suggested in ACI 347.3R-13. As noted in the ACI Guide: “The surface void ratio is only required to be determined if the entire impression of the surface does not meet the contract expectation.”

Using a mock-up to evaluate formed surface appearance is admittedly subjective. But it is superior to basing an evaluation on objective measurements that don’t necessarily relate to aesthetics.

Section 6.1.4.4 of ACI 301-16 contains detailed instructions for field mockups as follow:

“6.1.4.4.a Construct field mockups using same procedures, equipment, and materials that will be used for production of architectural concrete. Accepted field mock-up shall serve as the reference to which architectural concrete will be compared for periodic and final acceptance. Construct field mockups at an acceptable location on site. Provide a simulated repair area to demonstrate an acceptable repair procedure. Repair procedure shall be suitable to provide an acceptable color and texture match. Protect from physical damage and retain the mockups until final acceptance of architectural concrete.”

“6.1.4.4.b For formed architectural concrete surfaces, include vertical, horizontal, rustication joints, and any sculptured features. Demonstrate, color and texture. Cure the mock-up as intended with the structure. If required, apply sealers and coatings to only a portion of the mock-up. Construct mockup to include at least-two lifts having heights planned for placement of architectural concrete.”

When building mock-ups, contractors can’t duplicate all of the variables that affect the size, number, and concentration of bugholes.¹² They can, however, reduce effects of some of the variables when building the mock-up by avoiding the following mistakes:

- Using different personnel and production procedures for the mock-up than those to be used during building construction. Using a hand-picked crew of the best workers and telling them to take extra care on the mock-up is self-defeating. Given enough skills, time and money, most contractors can build an outstanding mock-up with some bugholes. But the goal is to achieve the architect/owner’s desired appearance for the completed structure, and nothing more.
- Using new forms for the mock-up, when it’s known that reuse of forms is planned for the structure. Constructing the mock-up with used forms is more realistic, because form facing materials have a major effect on bughole formation.
- Using only one truckload of concrete in the mock-up. Concrete from two truckloads will help to highlight any effects of batch-to-batch variations on bugholes.

Finally, architects and owners need to approve the whole mock-up rather than parts of it.¹⁹ If parts of it are not satisfactory, a new mock-up should be built. Contractors are first fully introduced to the specifier’s expectations when the mock-up is evaluated. Specifications can’t adequately describe the desired end result because acceptance is subjective. There is then a need to provide for fair compensation of the contractor when more than one mock-up is required.

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FIGURES

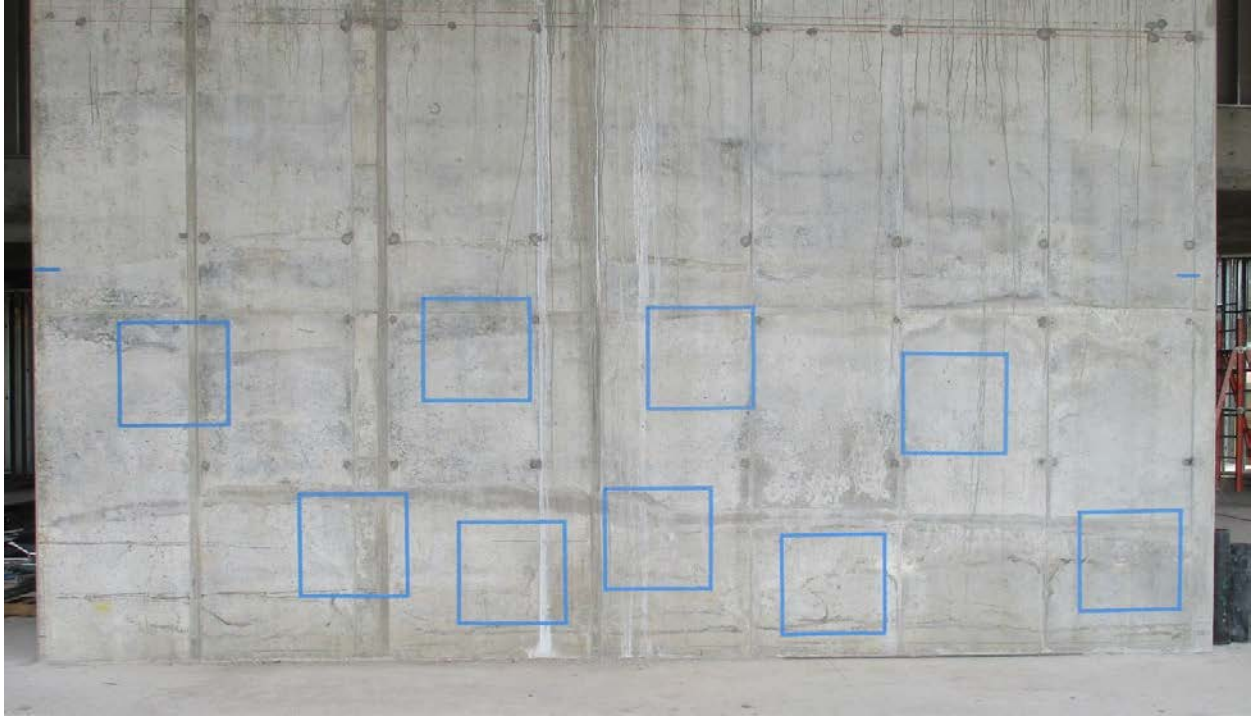


Fig. 1 Nine randomly chosen, 24 x 24-in. (610 x 610 mm) non-overlapping samples for measuring surface void ratio on a shear wall with an as-cast finish. (Credit: Paradigm Consultants, Inc.)

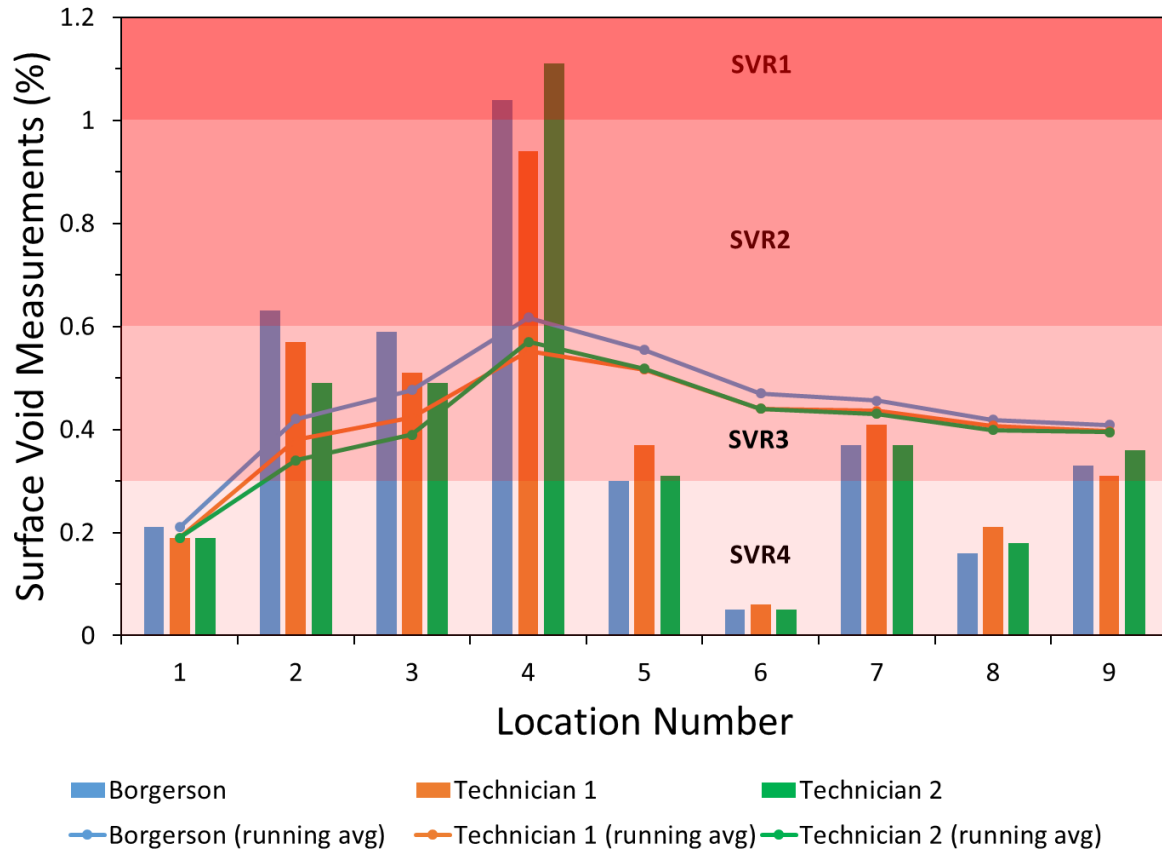


Fig. 2 Results of SVR measurements by three different testing laboratory employees. Note that the average SVR was 0.4%, which would place the wall in the SVR3 category. But also note also that individual results for the three measurements of each sample, due to differences in reproducibility, could have placed the wall in any of the four SVR categories.

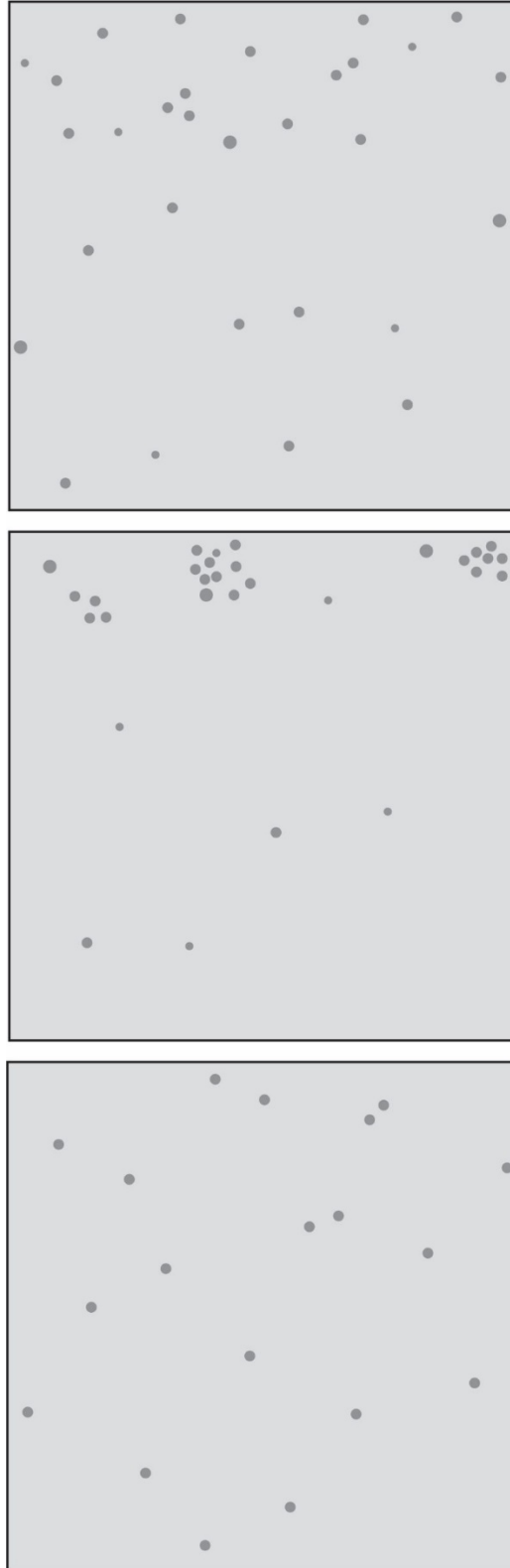


Fig. 3 Scale drawings for three patterns of varying size bugholes with identical ratios of void area to total surface area. SVR equals approximately 1.0%. Due to difference in symmetry and concentration of the bugholes, it is doubtful that all three patterns would be judged to be of equal aesthetic value.



Fig. 4 Photos of board-finished walls in an award-winning museum. Note the number and size of bugholes, which were considered by a panel of architects to be a pleasant aesthetic feature of the museum's interior. (Photos courtesy of the Herbert F. Johnson Museum of Art, Cornell University)

After Two Hundred Years of Estimating Evaporation, It Is Still a Mystery Kenneth C. Hover

Synopsis: PCA researchers interested in the problem of evaporation of bleed water from concrete surfaces borrowed an equation developed by hydrologists to predict evaporation from Lake Hefner in Oklahoma. PCA's graphical representation of that equation, subsequently modified to its present form by NRMCA, was later incorporated into multiple ACI documents, and is known by concrete technologists world-wide as the "Evaporation Rate Nomograph." The most appropriate use of this formulation in concrete construction is to estimate the evaporative potential of atmospheric conditions (known as "evaporativity"). Since the difference between actual and estimated evaporation rate can be in the range of $\pm 40\%$ of the estimate, best use of the equation as routinely applied is as a semi-quantitative guide to estimate risk of early drying and inform decisions about timing and conduct of concrete placing and finishing operations. Use of the "Nomograph" and related "Apps" in specifications is more problematic, however, given: 1.) the inherent uncertainty in its underlying equation, 2.) the difficulty in obtaining input data that appropriately characterize jobsite microclimate, and 3.) establishing a mixture-specific criterion for tolerable evaporation rate.

Keywords: Bleeding, Cracking, Curing, Drying, Evaporation, Finishing, Shrinkage, Weather

Ken Hover joined the faculty at Cornell University after 12 years of experience in the concrete industry. He is a member of ACI 305 and 306 on Hot and Cold weather concreting, and a past-chair of ACI 08 on Curing. He is an ACI Fellow and Past-President, and a Distinguished member of ASCE. At Cornell he is a Stephen A. Weiss Fellow and teaches reinforced and prestressed concrete design and concrete materials.

Introduction

The concrete industry became interested in the topic of evaporation following the pair of papers, first by Menzel [1954] and then by Lerch [1957], proposing that drying (and subsequent cracking) of a concrete surface is related to evaporation rate. Menzel's version was the more general of the two, stating: "Cracks from drying shrinkage are likely to develop soon after the rate of evaporation of moisture from the top surface of fresh concrete exceeds the rate at which moisture is supplied to the surface." This not only focused attention on evaporation, but introduced what ACI 308 [2016] now calls "initial curing" to externally provide moisture to offset evaporation of bleed-water. Thus motivated to find a way to estimate evaporation rates from measurements of ambient conditions, Menzel introduced the concrete industry to a predictive equation (and its graphical solution or "nomograph") that had been developed by Kohler [Kohler 1952] of the U.S. Geologic Survey for predicting evaporation from Lake Hefner in Oklahoma. Kohler's equation is empirical and approximate, but based on the physics of how water temperature, air temperature, humidity, and wind speed combine to influence evaporation from the surface of a body of water.

Kohler assessed his own work by saying that his results "cannot be considered to represent...evaporation from a nearby lake, but they do constitute an index to the evaporative power of the atmosphere." Thus, the equation has no intent or capacity to actually estimate the rate of evaporation of water from a concrete surface, but instead quantifies "Evaporativity" [Hillel 1971; Jalota 1998] which is the potential of the local, site-specific ambient atmospheric conditions to evaporate water from a body or pan of water at the temperature of the concrete in question. Menzel referred to the output of the equation as the "Drying tendency of the air" [Menzel 1954]. In concrete applications, at high levels of evaporativity (stated in units of lb. water/ft²/h, or kg/m²/h) the field crew needs to lower the risk of early surface-drying via initial curing by fog-spraying or use of evaporation reducers, erecting wind-breaks, cooling the concrete, changing proportions or ingredients, or shifting the dates or times of placing and finishing operations. In this advisory capacity, this well-known, borrowed equation has served the concrete industry well for over 60 years in the form of nomographs, wall posters, computer programs, and more recently APPS for mobile devices, and is an invaluable aid and guide to judgement and decision-making in the field.

The accuracy of the computed evaporation rate is nevertheless influenced by the assumptions, approximations, and uncertainties inherent to the development and application of the equation. These limitations become all the more important when employing the equation beyond its advisory capacity and using it as part of a specification, or when employing it in forensic investigations at some time after slab-cracking has occurred. For these purposes the specification writer, on-site inspector, forensic investigator, or expert witness must recognize the limitations of the precision and physical reliability of the Kohler's equation as borrowed by Menzel, and then include those limitations in their requirements, measurements, or conclusions. Having enthusiastically advocated use of the equation and its graphical interpretations, the author's purpose in this paper is to encourage appropriate use within technological limits by addressing 1.) Fundamental variability of results; 2.) Challenge in obtaining appropriate values for the input parameters, and 3.) Difficulty in setting criteria for a mixture-specific "tolerable rate of evaporation."

Background

Kohler's versions of Dalton's evaporation model

The history of the evaporation nomograph has been documented in detail by others, including Uno [Uno 1998] and Hover [1992, 2006], each referencing many primary sources. Given the recently renewed attention to use of the underlying equation, driven largely by the proliferation of electronic "Evaporation-APPS," it is useful to briefly review its development to highlight its intended use and limitations. In short, Carl Menzel [1954] adopted an empirical equation developed by Max Kohler [1952,1954] who had experimentally determined coefficients that he plugged-in to an approximate mathematical model proposed by John Dalton [1802] (Eqn. 1).

$$E = f(u) (e_s - e_a) \dots \dots \dots (1)$$

Where: E = rate of evaporation in user-defined units, $f(u)$: Function of wind speed (to be determined by user); e_s = saturation vapor pressure at temperature of evaporating water; e_a = vapor pressure of air above evaporating surface based on air temperature and relative humidity; units determined by user.

Dalton's model had been developed for estimating evaporation from lakes and reservoirs, and according to Brutsaert [1982] "Countless" site-specific empirical variants like Kohler's have been developed to fit Dalton's model to various bodies of water around the world, many of which are cataloged by Veihe Meyer [1964]. Kohler himself developed ten different equations for Lake Hefner, from which Menzel borrowed the one of interest here (eqn. 2). This expression estimated the daily loss of water due to evaporation, E , from a 6 ft. (1.8 m) diameter x 2 ft. (0.61 m) deep galvanized pan of water, partially sunken into the ground on the shoreline of Lake Hefner over a 15-month period in 1951 and 52. (Interestingly, by 1955 Kohler [1955] advocated yet another equation.)

Table 1. Kohler's [1952] Original Equation and Subsequent Equivalent in SI units.

$E = (0.253 + 0.0040V) (e_s - e_a) \dots \dots \dots (2)$	$E = (0.253 + 0.0025V) (e_s - e_a) \dots \dots \dots (3)$
where E = evaporation rate, inches of water/day e_s = saturation vapor pressure of water near the surface of the pan, inches-Hg e_a = saturation vapor pressure in the air at the temperature and humidity of the air, inches-Hg V = wind velocity, miles/day	where E = evaporation rate, mm water/day e_s = saturation vapor pressure of water near the surface of the pan, mm-Hg e_a = saturation vapor pressure in the air at the temperature and humidity of the air, mm-Hg V = wind velocity, km/day

Accuracy and precision of Kohler's equation

As discussed later for concrete applications, Kohler defined a site-specific protocol for how and where to take measurements for wind speed, air temperature and dew-point, and the near-surface temperature of the water. The water level in the pan was maintained at about 2 in. (50 mm) below the rim, with a thermometer floating in the top ½ inch (12 mm). Recorded data included: 1.) Mean 24-hour daily average saturation water vapor pressure at the water surface, e_o , computed from the average of the maximum and minimum surface-water temperature recorded over the 24 hours *preceding* the day in which pan-evaporation was recorded; 2.) Mean 24-hour daily average water vapor pressure in the air computed from wet- and dry-bulb temperatures averaged over the day, measured at about 5 ft. (1.5m) above the surface of the water in the pan, e_a ; and 3.) Mean 24-hour wind speed, V , recorded at about 20 inches (0.5 m) above the surface of the water in the pan. All temperatures and humidity were measured in the shade.

When supplied with data collected in strict accordance with this protocol, averaged over any given 24-hour period, Kohler's equation estimated the measured daily rate of evaporation from the pan to within $\pm 38\%$ at the 95% confidence level. In any given month, the cumulative evaporation from the pan estimated the cumulative evaporation in the adjacent lake within a 47% overestimate to a 56% underestimate. When used to estimate cumulative evaporation of Lake Hefner over an entire year, however, averaging all daytime, nighttime, and seasonal variations, cumulative pan evaporation overestimated lake evaporation by only 10%. This suggests that short-duration peaks in evaporation rate had limited influence on long-term averages, and that short-term over- and under-estimates tended to balance-out over the long term. For hydrologists studying long-term trends within the context and accuracy of regional climate predictions, these were useful results. In the context of quantifying risk of early-age drying during the much shorter duration of concrete placing, finishing, and curing, estimating 24-hour average evaporation rate to an accuracy of $\pm 38\%$ may be less useful, especially if used to evaluate compliance with specifications. This will be discussed further.

Menzel's contribution

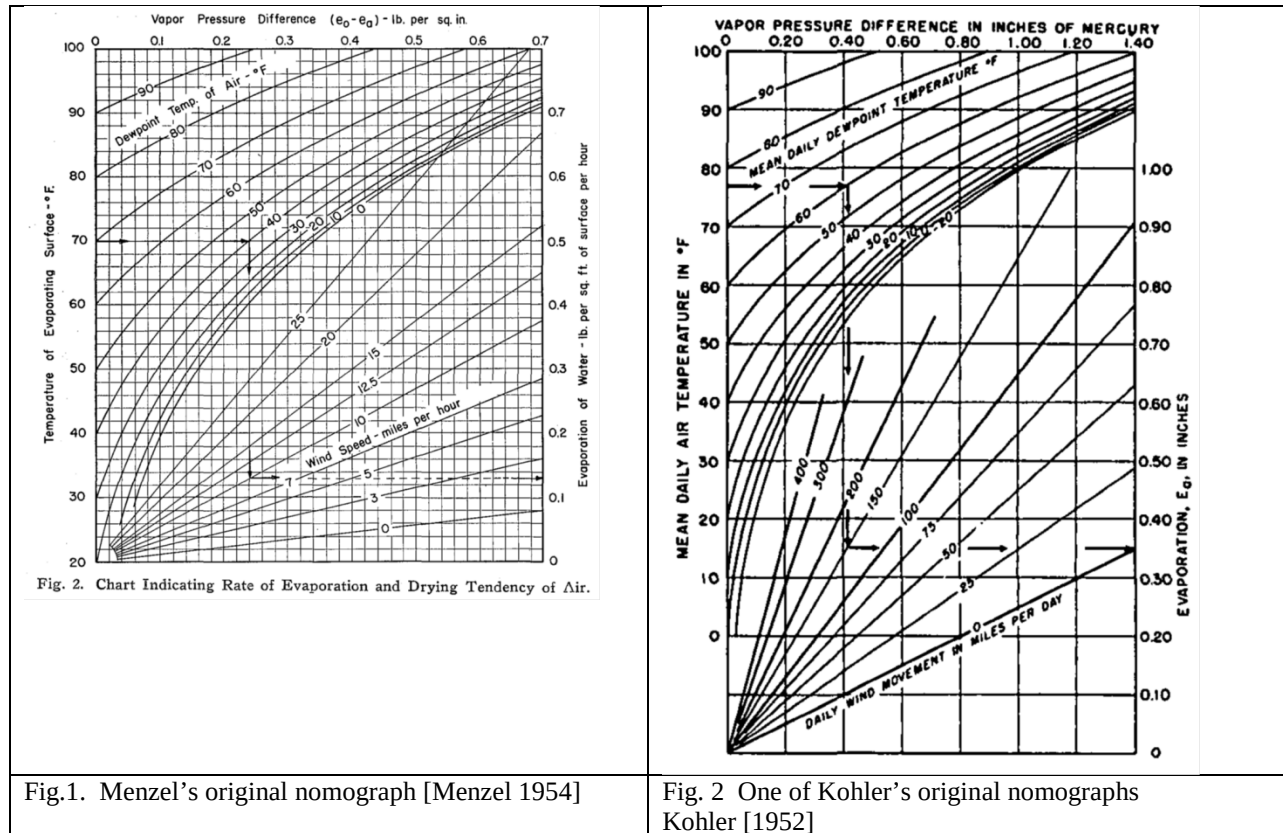
In proposing adoption of this approach to concrete, Menzel [1954] assumed that evaporation from a concrete surface covered with bleed-water (to some unspecified depth) would proceed just like water evaporating from Kohler's pan or Lake Hefner. Menzel was careful to describe the output of the equation as an estimate of the "Drying tendency of air," (or as more formally termed "evaporativity"), and at no point explicitly equated drying tendency with the actual rate of evaporation from the concrete surface, although this may be inferred from his comparisons of drying tendency with bleeding rate. Menzel was silent, however, on actual or implied rate of evaporation from recently placed concrete *after* bleed-water is no longer visible, since the equation applies only to evaporation of water from a body of water, not from a saturated, porous substance. Menzel's only modifications to Kohler's equation were to change units from: a.) evaporation in inches per day to lb/ft²/h; b.) input vapor pressure from inches of mercury to lb/in²; and c.) change wind speed from miles per day to mph. Finally, while Menzel's input instructions refer to temperature at the "evaporating surface," the balance of his paper refers to "concrete temperature." He thus tacitly assumed that the temperature of the evaporating bleed-water at the surface could be taken as the concrete temperature, measured at some unspecified depth by some unspecified method. Thus, Menzel published what would be more correctly called the "Kohler-Menzel" equation (Eqns. 4&5), accompanied with a graphical solution or "nomograph," [Figure 1] likewise adapted from Kohler [Figure 2] with the changes in units-of-measure described above.

Table 2. Menzel's [1954] unit-conversions from Kohler's [1952] Equation and Subsequent SI Equivalent

$W = 0.44 (e_o - e_a) (0.253 + 0.096V) \dots\dots\dots(4)$	$W = 0.042 (e_o - e_a) (0.253 + 0.060V) \dots\dots\dots(5)$
where W = evaporation rate, lb/ft ² /h e_o = saturation vapor pressure of water near the surface of the pan, lb/in ² e_a = saturation vapor pressure in the air at the temperature and humidity of the air, lb/in ² V = wind velocity, miles/h	where W = evaporation rate, kg/m ² /h e_o = saturation vapor pressure of water near the surface of the pan, mm-Hg e_a = saturation vapor pressure in the air at the temperature and humidity of the air, mm-Hg V = wind velocity, km/hr

Table 3. Uno's[1998] integration of WMO Vapor Pressure into Kohler-Menzel, and SI Equivalent.

$E = (T_c^{2.5} - r \times T_a^{2.5})(1 + 0.4V) \times 10^{-6} \dots\dots\dots(6)$	$E = 5([T_c+18]^{2.5} - r \times [T_a+18]^{2.5})(V+4) \times 10^{-6} \dots\dots\dots(7)$
where E = evaporation rate, lb/ft ² /h T _c = concrete (water surface) temperature T _a = air temperature r = relative humidity (expressed as a fraction) V = wind velocity, mph <i>Note that the precision of the coefficients in this equation is limited to one significant figure, .i.e., 0, 0.1, 0.2, 0.3 lb/ft²/h</i>	where E = evaporation rate (kg/m ² /h T _c = concrete (water surface) temperature T _a = air temperature r = relative humidity (expressed as a fraction) V = wind velocity, kph <i>Note that the precision of the coefficients in this equation is limited to one significant figure, .i.e., 0, 1, 2, 3 kg/m²/h.</i>



Uno's contribution

The Kohler-Menzel equation was made more useful in 1960 when NRMCA [1960] converted air temperature and dew-point to air temperature and humidity, and on the suggestion of NRMCA member J.R. Howard, reformatted the graphic solution to make it easier to use. The result was the currently familiar version of the "Nomograph" [NRMCA 1960] seen in Figure 3. Prior to Uno's important paper [Uno 1998], a key step in the calculation for Kohler and Menzel was finding the saturation vapor pressure of water in the air, and at the bleed-water surface, as a function of temperature. This relationship was built-in to graphic solutions (as embedded in Figs. 1-3 and shown in Fig. 4), but for those who wanted to calculate the value, a lookup table was required such as published by The Chemical Rubber Press [CRC 1987] or as included in earlier versions of ACI documents such as ACI 305.1-06 [ACI 305 2006]. When Luke Snell pioneered a computer program for solving the Kohler-Menzel equation in 1984 [Snell 1984], he generated his own curve-fit for vapor pressure. In 1998 Paul Uno [Uno 1998] brought to our attention an improved curve-fit for the saturation vapor pressure of water used by the World Meteorological Organization (WMO, a specialized agency of the United Nations) [Tetens, 1930, Murray, 1967, Dilley, 1968, Mills, 1975]. Uno then incorporated the WMO equation into Kohler-Menzel, permitting faithful replication of results using Kohler-Menzel without the need for tabulated vapor pressure [Uno 1998; ACI 305 2010]. The resulting "Kohler-Menzel-Uno" equations (Eqns. 6&7) were adopted in ACI 305's Guide to Hot Weather Concreting [2010], and have become the basis of a number of handy "APPS" generated by many organizations, including ACI.

Underlying Principles

Dalton's "Law"

Dalton proposed that evaporation rate is linearly proportional to the difference in water-vapor pressure between the evaporating surface and the ambient air. (That "Dalton's Law" was an oversimplification was well known by

Kohler and his predecessors [Kohler 1952, 1954, 1955]. Improving on Dalton's simplified model continues to be a subject of research [Jones 1991; Tang and Etzion 2004; Abteu & Melesse 2013].) Nevertheless, the vapor pressure at the evaporating surface is taken to be the saturation vapor pressure of pure water at the temperature of that surface, which as can be seen in Fig.4, varies sharply with temperature, approximately doubling with each 20F (11C) increase in water temperature. The pressure of water vapor in the ambient air above the evaporating surface is the saturation vapor pressure at the temperature of the air, multiplied by relative humidity. When vapor pressure at the surface exceeds that of the air, evaporation occurs; the reverse condition leads to condensation. Kohler (and others) recognized that solar radiation also provides energy that drives evaporation, (a factor ignored by Dalton) and therefore developed two sets of equations, with and without accounting for solar heating. Menzel adopted one of the simpler "water-temperature" equations for which Kohler's (and Menzel's) data-acquisition protocol require that air- and water-temperature and humidity be measured "in the shade." Kohler's more complex equations accounted for incident radiation, but without significant change in accuracy for long-term evaporation measurements because solar energy warms the water deeper than the just surface over a long-enough exposure time [Kohler 1955]. This energy storage then contributes to increased evaporation later.

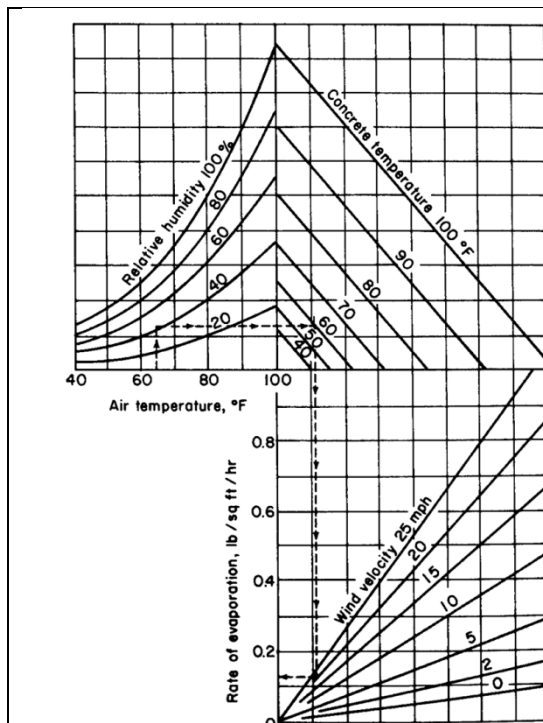


Fig. 3 The more familiar version of the Kohler-Menzel evaporation nomograph for estimating the maximum potential rate of evaporation of the environment, assuming a water-covered surface in which the water temperature is equal to the concrete temperature. (As reformatted by NRMCA [1960]).

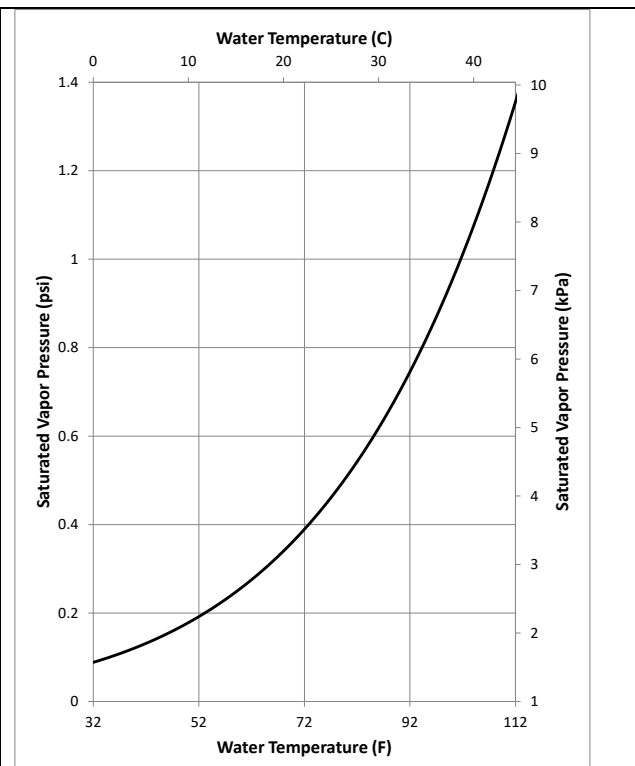


Fig. 4. Saturation vapor pressure of water over a range of temperatures encountered in concrete construction. Adapted from [Uno, 2002].

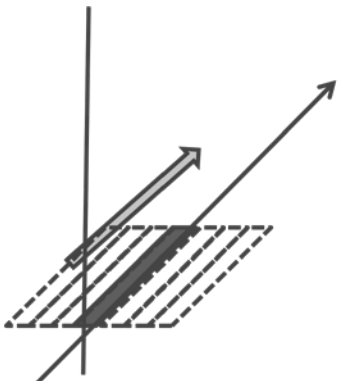
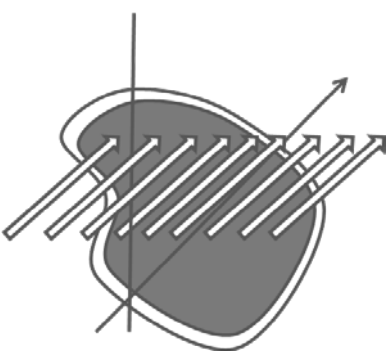
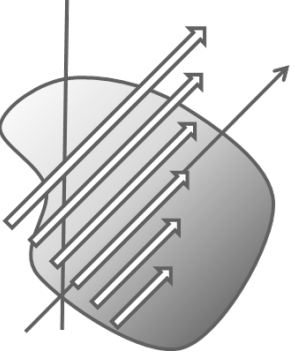
Effect of wind

Wind is a critical factor because evaporating water molecules accumulate in the air near the water surface when the air is still, locally increasing relative humidity and inhibiting further evaporation. The faster the wind speed near the evaporating surface the more the evaporated water molecules are dispersed and moving air at its drier, “upwind” humidity is in direct contact with that evaporating surface. This is why Kohler’s protocol requires measuring relative humidity upwind of the evaporating surface. (A similar effect is experienced when casting a concrete slab in an enclosed space: air in the enclosure becomes more humid as placing and finishing operations continue. The same does not happen outdoors in a breeze. This is also why temporary wind-breaks can lower risk of early age drying.) While the general influence of wind is logically understandable, the fundamental problem is how to characterize the effect of the wind given that wind speed fluctuates rapidly over time and location. Wind speed likewise varies with height above the evaporating surface in accordance with a “wind speed profile” that depends on atmospheric conditions, topography, surface roughness, and ground clutter. Amid these variables, which can all change dramatically over the short duration of concrete placing and finishing, the challenge is to measure a characteristic “wind speed” that effectively captures all of these effects.

The wind speed that really matters is the velocity at a fraction of an inch (a few mm) just above the evaporating surface, since that is where the evaporated water vapor molecules initially congregate. (This is why a modern “floor-drying fan” that directs a wide, shallow airstream parallel and adjacent to the floor surface dries that surface more efficiently than a traditional box-type, rotary fan elevated above the floor.) Any value of wind speed used in computing evaporation rate therefore has to have a known and reliable relationship to the wind speed near the evaporating surface. (While Kohler never knew the actual wind speed just above the water surface, he determined the effect that the wind had on evaporation when he knew its speed at 20 inches (0.5m) above that same surface. He then built that relationship into the coefficients in his equation. He minimized further complications by conducting his entire experimental program over flat, uncluttered terrain.) Rationally accounting for the powerful effect of wind posed a challenge that not even John Dalton was up to, so Dalton proposed only that some undefined function of wind would impact evaporation, leaving the details to others. (In Dalton’s own experiments he used 3 “wind speeds,” classified as “indoors with windows closed,” “indoors with windows open,” and “out-of-doors” [Brutsaert 1982].) We shall return to the difficulty in measuring wind speed.

Another complication is that all evaporation equations based on Dalton’s and similar approaches envision a two-dimensional model of a body of water (or water covered surface) as a series of parallel strips of water surface of unit width, with uniform wind air temperature, and humidity over the width of that strip as in Figure 5a. In such a model the actual size or shape of the evaporating surface does not matter. Even if conditions were to remain constant, a body of water with a more realistic shape is likely to dry more rapidly at the edges because of contact with drier air, and this would increase relative evaporation rate for smaller bodies of water (Fig. 5b). Brutsaert & Yeh [1970] and Tang & Etzion [2004], cite area of the evaporating surface as a variable in the 3-dimensional problem of evaporation, with Brutsaert showing that evaporation rate is inversely proportional to the area of evaporating surface raised to a power. On any given day with realistically uniform ambient conditions, the rates of evaporation per unit area from a large lake or pond will be less than that from a nearby Olympic-size pool, which will be less than that from a children’s inflatable wading pool. By extrapolating Brutsaert’s [1982] equation for correcting for the area-effect, one calculates that for all other factors remaining equal, and assuming applicability of Kohler to concrete, the evaporation rate from a water-covered concrete slab, 5400 ft² in area¹ (500 m²) would be about 70% of the rate obtained from Kohler’s equation developed for a single 28 ft² (2.6 m²) galvanized pan on the shore of Lake Hefner. (This value corroborates the rule-of-thumb that evaporation rate from a lake or reservoir will be about 70% of the evaporation rate from a 4 ft (1.2 m) diameter, “Class A” evaporation pan on the shore [Pan area= 12.3 ft² (1.14 m²) [Kohler 1952,1924, 1955].) Ambient conditions will rarely be uniform over an evaporating reservoir or a large concrete slab, however. As the evaporating surface gets larger or more irregular other problems include the likelihood that ambient conditions, and perhaps even the water temperature, will vary over the surface. This will result in a spatially variable rate of evaporation over the body of water in question.

¹ 5400 ft² (500 m²) is the surface area of a 100 CY (76 m³) slab, 6-inches (150 mm) thick.

		
Fig. 5a. Assumed two-dimensional evaporation over parallel strips of unit width, uniform ambient conditions.	Fig. 5b. Three-dimensional evaporation over an irregular water surface, uniform ambient conditions.	Fig. 5c. Three-dimensional evaporation over an irregular water surface, non-uniform ambient conditions.

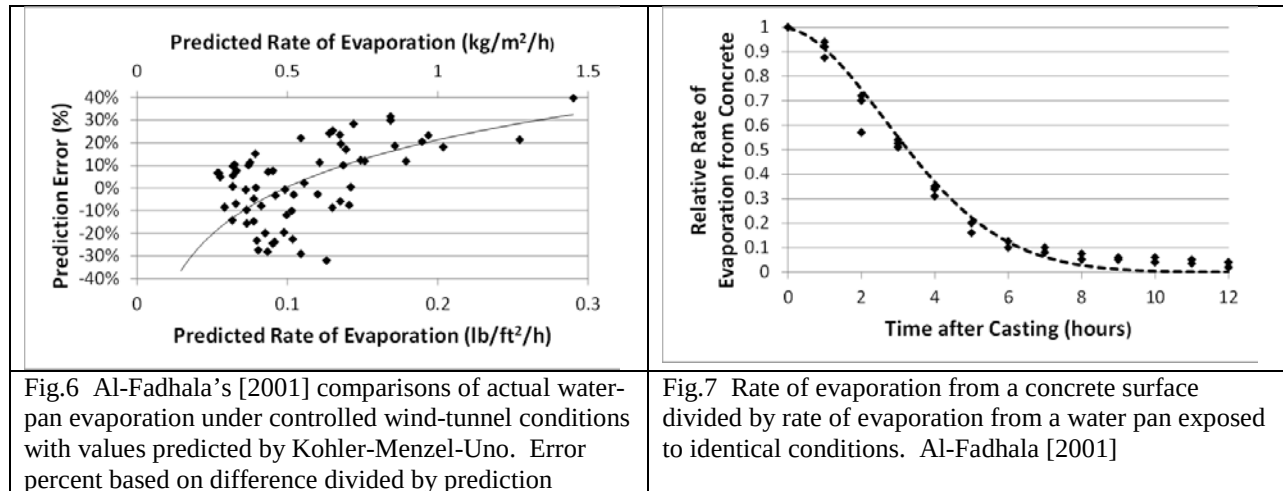
These complications notwithstanding, in applying Kohler's work to concrete it is instructive to recognize that over the 15-month course of his Oklahoma experiment the average rate of evaporation from Kohler's small galvanized pan was less than $0.05 \text{ lb/ft}^2/\text{h}$, (0.24 kg/m^2) with an average wind speed of about 5 mph (2.2 m/s). As will be discussed, these averages would suggest relatively benign conditions for most typical concrete mixtures. But these averages are deceptive as they do not capture the peak, short-term evaporation that would have occurred due to short gusts of wind and transient values of temperature and humidity. [Even though Kohler's equation was most accurate when applied to the annual average evaporation, one cannot assume limited risk of plastic shrinkage cracking when placing and finishing concrete in Oklahoma just because the average annual evaporation rate was less than $0.05 \text{ lb/ft}^2/\text{h}$, (0.24 kg/m^2).]

In evaluating his own development of the equation that we have inherited, Kohler [1954] wrote "it seems appropriate to emphasize the 'inconclusive' nature of a single evaporation experiment, at least with respect to the pan approach. The Lake Hefner experiment has undoubtedly provided the most reliable data available in an over-all sense, and has gone far in providing substantiating evidence. Nevertheless, additional similar experiments must be performed under other climatic regimes before the reliability of the empirical approaches described can be accurately determined."

Accuracy when applied to concrete applications

Al-Fadhala's Experiments

To better understand the accuracy of Kohler's equation when applied to recently cast concrete, Al-Fadhala [2001] performed a comprehensive series of water pan-evaporation tests in a wind tunnel with controlled, uniform ambient conditions. Achieving measured evaporation rates varying from -0.1 (condensation) to $+0.30 \text{ lb/ft}^2/\text{hr}$, [$-.05$ to $1.5 \text{ kg/m}^2/\text{h}$] Al-Fadhala observed that under her conditions the Kohler-Menzel-Uno equation overestimated pan-evaporation by 10 to 40% at evaporation rates greater than $0.15 \text{ lb/ft}^2/\text{hr}$ ($0.73 \text{ kg/m}^2/\text{h}$). [See Figure 6.] In the range of 0.05 to $0.15 \text{ lb/ft}^2/\text{hr}$ (0.24 to $0.73 \text{ kg/m}^2/\text{h}$), the error was about $\pm 30\%$ of the predicted value. Al-Fadhala's estimates of uncertainty are not significantly different from Kohler's when converted to a 95% confidence interval of about $\pm 40\%$.



When comparing evaporation from concrete to evaporation from an adjacent pan of water under identical conditions, Al-Fadhala reported close agreement during a period of ½ hour or less, as long as bleed-water was visible on the concrete surface [Figure 7]. This observation generally supports Menzel's use of estimated pan-evaporation as a proxy for estimated bleed-water evaporation, but only while the concrete surface is covered with bleed-water. For her concrete mixtures and conditions, surface evaporation dropped exponentially to about 50% of pan-evaporation rate by 3 hours after casting. As bleed-water evaporates, the actual evaporation rate at the concrete surface diminishes since it requires increasingly more evaporative power to extract water from the pores of any drying, porous medium. (A saturated sponge dries more slowly than a thin layer of water on the adjacent countertop.) This same phenomenon was studied in detail by Tang & Etzion [2004], concluding that Dalton's simple linear expression is not strictly applicable to the wetted, porous surface. A very interesting result from their study as it may apply to concrete applications, however, is that even though evaporation from a wet, porous surface is less than from a water-covered surface, the influence of wind can be more severe for rougher surface textures than for a smooth body of water. In the author's first field-experience with plastic shrinkage cracking, cracks appeared immediately upon applying a deep-tined finish to a parking-garage slab. While this observation may or may not corroborate Tang & Etzion, there is no question that tined, raked, broom, or swirl finishes significantly increase the exposed surface area of recently cast concrete, and if the business of evaporation rate prediction were as scientific as we wish, we might one day vary evaporation rate criteria not only for bleeding characteristics of the mixture, but also for surface texture.

Variability of input parameters

Both Kohler's original work and Al-Fadhala suggest an uncertainty in the range of $\pm 40\%$ of the predicted value (at the 95% confidence level) when using the Kohler-Menzel-Uno equation to estimate rate of bleed-water evaporation. As rough as this is, it may be a lower-bound uncertainty because of the high standard of control in the two experimental programs. Al-Fadhala had ideally precise control of an indoor wind tunnel with conditioned air and unvarying ambient conditions for the 12-hour duration of her experiments. Kohler had natural conditions, but all environmental variables were averaged over a period of one day, with water temperature taken as the average of daily max and min, and wind speed averaged as miles per day. (Recall that the pan over-estimated one-year average evaporation from the lake by only 10%.) No data concerning short-term spikes in evaporation in response to changes in sunshine, humidity, temperature, or wind were reported, nor could they be. While this greatly simplified Kohler's analysis, it is impossible for us to similarly smooth ambient data for application to concrete applications. Regional climate effects are measured in terms of seasonal and annual precipitation and evaporation, and the accuracy of Kohler's equation would be evaluated hydrologically on such terms. For our purposes, however, bleed-water typically covers the surface of concrete for an hour or less (as identified by the appearance and disappearance

of the visible “sheen”). On the concrete job-site daily averages of temperature, humidity, and wind speed would be of very little value. Besides, by the time a daily average could be computed, the concrete would have already exhibited early cracking or the lack of early cracking. Overall uncertainty in the estimate of evaporation rate therefore increases beyond Kohler’s prediction error when making predictions on the basis of short-term, highly variable data without benefit of long-term averages. Uncertainty increases again when the short-term data collection is not carried out in strict adherence to Kohler’s protocol for obtaining field data, as addressed in the next section. When using Kohler-Menzel-Uno to estimate evaporation rate, therefore, being within ± 30 to 40% of the actual evaporation rate is about as close as we can get, and much higher prediction error is likely.

DATA ACQUISITION AND PRECISION

Algebraic sensitivity of the Kohler-Menzel-Uno Equation

Before discussing the sources of variability and error for input values of ambient conditions and bleed-water temperature, it is useful to examine the purely algebraic sensitivity of the Kohler-Menzel-Uno. Consider the example that Menzel [1954] generated, for which $T_c=70F$, $T_a= 60F$, $RH=50\%$ (originally expressed as dew-point rather than T_a and RH), and $V_{wind}=10$ mph. For these input data the Kohler-Menzel-Uno equation computes water pan-evaporation rate of 0.14 lb/ft²/h (0.068 kg/m²/h). Figure 8 explores the results of varying each of these input parameters by ± 5 units relative to Menzel’s original values. Quantitative details are shown in Figures 8a-d, with the range of difference in computed evaporation rate associated with these modest variations ranging from $\pm 40\%$ for wind, $\pm 20\%$ for bleed-water temperature, ± 5 to 20% for air temperature, and 2 to 10% for relative humidity. (Other values would be obtained for different sets of starting-point data.) Small changes in input are magnified into large differences in output due to the exponential relationship between water temperature and vapor pressure (Fig. 4), and the wind velocity term that doubles evaporation between $V_{wind} = 0$ and $V_{wind} = 2.5$ mph (1.1 m/s). This same term increases evaporation by a factor of 10 between $V_{wind} = 0$ and $V_{wind} = 22.5$ mph (10.0 m/s).

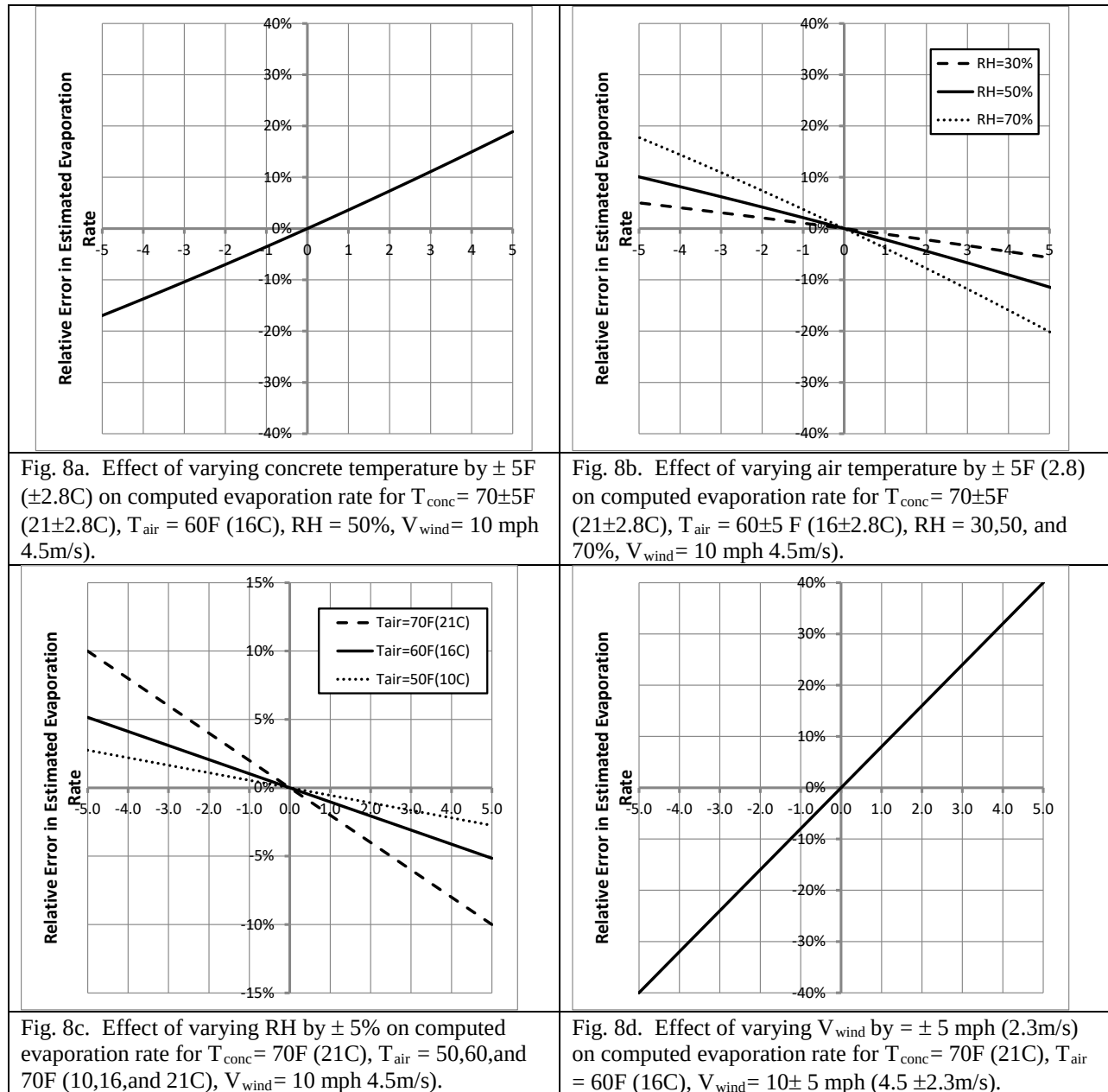
While the differences shown in Fig. 8 represent variations on a single parameter while all else is held constant, it of interest to explore combined effects. Table 4 shows the most and least severe combinations of the ± 5 -unit variations in Fig. 8. Such modest differences in ambient conditions and bleed-water temperature are responsible for computed evaporation rates that range from about 1/3 to double Menzel’s initial value.

Table 4. Influence of 5-unit variations in input parameters on computed evaporation rate. (Arrows indicate direction of change.)

Case	T conc	T air	RH	V _{wind}	Computed Evaporation Rate	Relative Evaporation Rate
Menzel Base	70F (21C)	60F (16C)	50%	10 mph (4.5 m/s)	0.14 lb/ft ² /h (0.7 kg/m ² /h)	1.00
Severe Case	75F (24C) ↑	55F (13C) ↓	45% ↓	15 mph (6.8 m/s) ↑	0.27 lb/ft ² /h (1.4 kg/m ² /h) ↑	2.00 ↑
Benign Case	65F (18C) ↓	65F (18C) ↑	55% ↑	5 mph (2.3 m/s) ↓	0.046 lb/ft ² /h (0.023 kg/m ² /h) ↓	0.34 ↓

To the degree that the equation approximately represents the actual physics of evaporation, a great deal can be learned from the interactions in Table 4. For example, the most severe variant of Menzel’s example could realistically result from actual changes in ambient conditions or concrete temperature over a concreting operation, or could be caused by inaccuracy in the measurements of those same ambient conditions. This more severe variant also correctly illustrates how cooler weather can bring the most aggressive drying. In many regions cooler weather brings lower air temperature, lower humidity, and faster wind. As air temperature continues to drop, sooner or later

specifications will require that the concrete be heated, which will further increase evaporation, as shown here for the detrimental combination of warmer concrete and cooler air. In the more benign case the example shows how just as quickly a small increase in air temperature and humidity, slower wind, and slightly cooler concrete dramatically reduce evaporation rate. The algebra of the equation therefore demands input that accurately represents the specific site and micro-meteorological conditions at the particular time of interest, and in the manner prescribed by Kohler.



As will be discussed, the broad range of estimates of evaporation rate demonstrated in this example could be the result of: actual variations over time during concreting; spatial variations on site conditions; within-batch or batch-to-batch variations; inherent variability and imprecision in measurements; differences in measuring method; or even greater differences in ambient conditions between the site and an off-site weather station.

The Kohler protocol revisited

Beyond the ± 30 to 40% error associated with the Kohler-Menzel-Uno equation when used in accordance with developer's protocol, additional uncertainty is introduced when the jobsite parameters inserted into the equation have not been obtained as Kohler required. As introduced previously, concrete temperature must represent temperature of the bleed-water on the concrete surface, in the shade. Air temperature and humidity must be taken at about 5 ft (1.5m) above and upwind of the evaporating surface, in the shade. Relevant wind speed is taken at about 20 in (0.5m) above the evaporating surface, regardless of its elevation above or below ground.

A critical factor, especially given the ease with which modern electronic devices make it possible to import weather data from weather stations at various distances remote from the site of concrete placement, is that all of Kohler's air temperature and humidity data were collected in a small weather-bureau instrument shelter that was 48 ft (14.6m) from the center of his water pan, and wind speed data were collected 21 ft (6.4m) from the center of the same water pan. Menzel included Kohler's procedural instructions in his 1954 paper, which were unfortunately omitted in NRMCA's more broadly distributed version [1960], but restored in more recent ACI documents [ACI 305 1999; ACI 308 2001]. Within the concrete community it has not generally been published or recognized, however, that the ambient data upon which Kohler's equation was based were intimately site-specific, with recording instruments less than 50 feet from the evaporating surface. It is important to recognize that adherence to these almost ritualistic procedures is not required because of any unique sanctity in Kohler's protocol. It is because the coefficients in the Kohler-Menzel-Uno equation were determined from data as Kohler collected them. A change in the data-collection protocol may at some point be warranted, but such will require a research project to recalibrate new coefficients.

Measuring bleed-water temperature

When Menzel substituted concrete temperature for Kohler's water temperature (implying that concrete temperature = bleed-water temperature) he prescribed no method for obtaining that temperature, leaving many with the default assumption that concrete temperature taken in routine Q/C testing via ASTM C1064 (in the wheelbarrow) is satisfactory [ASTM 2017] for this purpose. The problems here begin with the variability of the test method combined with the variability of concrete temperature itself. From 1990 to 2008 Hover [2013] conducted an annual field test for the Federal Highway Administration that monitored, among other parameters, the temperature of fresh concrete per ASTM C1064, as sampled about 30 times from a single concrete truck. A key finding for this current discussion was an average 4% coefficient of variation on concrete temperature (F) over 14 separate tests, concluding with a recommendation for a $\pm 5^\circ\text{F}$ (2.8°C) tolerance on specified concrete temperature. (Recall that a $\pm 5^\circ\text{F}$ (2.8°C) variability of bleed-water temperature shown in the example above caused a $\pm 20\%$ difference in computed evaporation rate. This $\pm 20\%$ difference could therefore be the result of a $\pm 5^\circ\text{F}$ (2.8°C) variation in as-measured concrete temperature within a single truck.)

A second problem in equating concrete temperature with bleed-water temperature is that C1064 requires 3-in (75 mm) penetration of the temperature probe. The test method includes instructions to "...prevent ambient air temperature from affecting the reading." For evaporation purposes, it is exactly the surface temperature *as affected* by ambient air temperature (and sunshine) that matters. Furthermore, there is no standard method for obtaining concrete temperature at the surface². Thus, surface temperature could be overestimated if T_c was obtained via

² The author recommends against using infrared remote sensors for measuring concrete surface temperature for specification compliance for at least three reasons. First, the thermal emissivity of concrete is variable with mixture, time, and angle of observation. Second, if bleed water is on the concrete surface, the thermal emissivity is that of water and not of concrete. Third, infrared sensors indiscriminately detect all emitted and reflected thermal radiation, regardless of whether it is from the concrete itself, the sun, heat from the engines of nearby construction equipment, or reflections from other sources of light and heat.