A contribution from ACI Committee 123, Research and Current Developments

From Research to Reality

Can we implement performance-based specifications for durability and longevity of concrete? Will they work?

by Tom Yu, Casimir J. Bognacki, Karthik H. Obla, James K. Hicks, Matthew D. D'Ambrosia, W. Jason Weiss, Tengfei Fu, and Eric R. Giannini

Concrete specifications have historically been prescriptive instructions to the contractor, defining not only mixture proportions but also means and methods. In contrast, performance-based specifications can provide the contractor and concrete producer with incentives to develop innovative concrete mixtures. Because the performance model is an alternative that is more related to how the concrete will perform over its service life, performance specifications can also lead to enhancements in the sustainability of concrete construction.

ACI Committee 329, Performance Criteria for Ready Mixed Concrete, seeks to work with ACI Committees 301, Specifications for Structural Concrete, and 318, Structural Concrete Building Code, to incorporate alternative, performance-based language in those committees' specification and code documents. Both ACI 301-16[1] and ACI 318-14[2] address durability requirements based on exposure classes for freezing-and-thawing, chloride-induced corrosion, and external sulfate attack. These requirements are drawn from, but are not completely consistent with, recommendations in ACI 201.2R, "Guide to Durable Concrete,"[3] and are primarily prescriptive in nature—for example, maximum water-cementitious material ratio (*w/cm*)—and are not correlated to any specific service life. Acceptance of ready mixed concrete per ACI 318-14 and ACI 301-16 primarily remains reliant on measurements of slump, air content, and compressive strength rather than measurable durability performance criteria (for example, permeability, resistivity, and drying shrinkage potential).

Currently, ACI Committee 329 is developing a new guidance document for writing performance-based guide specifications. This may serve as a basis for performance-based language for durability to be added to ACI specifications and codes, including ACI 301 and ACI 318, either by reference or as a supplemental alternative to the current prescriptive approach. ACI Committee 201, Durability of Concrete, is also exploring the development of a model specification or code document for durability that may benefit from the work in progress by ACI Committee 329.

The ACI 301 Specification[1] and ACI 318 Building Code[2] are particularly important documents because together they often form the basis for model and local building codes and project specifications. An increase in the use of performance-based language in these documents is likely to lead to increased implementation in practice. However, changing these documents and their associated ASTM standards is a rigorous, consensus-based process that demands acceptance by committees balancing the interests of concrete producers, consumers, and the general public. ACI 318, in particular, is tasked with establishing the minimum requirements for structural concrete from a life safety perspective; any changes to the mandatory language document must be in support of that mandate. To implement performance specifications, many groups must be confident that the specifications will result in successful execution. The primary questions are:

- Can the concrete industry implement performance-based specifications?
- Will performance-based specifications ensure durability and longevity?

A panel of experts, several of whom serve on ACI Committee 329, debated these questions during the 123 Forum session at The ACI Concrete Convention and Exposition – Spring 2016 in Milwaukee, WI, on April 18, 2016. Eric Giannini and Tengfei Fu organized and moderated the session. The panelists included Tom Yu, Federal Highway Administration (FHWA); Casimir Bognacki, Port Authority of New York & New Jersey (PANYNJ); Karthik Obla, National Ready Mixed Concrete Association (NRMCA); two consulting engineers—Matthew D'Ambrosia, CTLGroup, and James Hicks, Hicks Engineering; and W. Jason Weiss, Oregon State University. This article is a summation of the ideas presented and discussed by the panelists.

The panel was not in complete agreement on all facets of the implementation of performance-based specifications. Yu discussed FHWA efforts to encourage the implementation of performance-based specifications by state departments of transportation (DOTs). Bognacki and the PANYNJ stated that some degree of prescriptive specifications remain relevant and necessary, and challenged the idea put forth by Yu and Obla that performance-based specifications would encourage innovation and quality control improvements by producers. D'Ambrosia and Hicks discussed opportunities and challenges associated with the development and implementation of performance-based specifications, and Weiss offered a proposed framework for a performance-based approach to specifying durability.

USDOT's Perspective

The U.S. FHWA encourages innovation programs that deploy and promote pavement technologies and practices that improve performance, cost-effectiveness, safety, and user satisfaction. These programs are specifically required by the Moving Ahead for Progress in the 21st Century Act (MAP-21)[4] and continued under the Fixing America's Surface Transportation (FAST) Act.[5] Durable concrete is essential to achieving long-life concrete pavements. Making durable concrete may involve the use of supplementary cementitious materials (SCMs) and chemical admixtures that can also enhance the sustainability of concrete by reducing the environmental impact and life-cycle costs associated with concrete construction. In many parts of the United States, the use of recycled concrete aggregate (RCA) is under greater consideration for a wider range of projects because of the dwindling supply of quality virgin aggregate. Depending on the quality of the RCA, it may be possible to make concrete meeting desired durability performance targets, even if they are not yet permitted by many project specifications. In fact, many specifications currently in use are not designed to accommodate the wide range of materials combinations capable of producing more durable and sustainable concrete. An elegant solution is to use a performance specification, allowing improvements in durability, cost-effectiveness, and sustainability, while also giving contractors the freedom to be innovative.

The question surrounding performance specifications is whether the tools are available today for implementation. The key to answering this question is recognizing that the ultimate goal is to improve the quality of concrete, not to initially implement a completely performance-based specification. In current practice, only the mechanical properties of hardened concrete (primarily strength) are commonly measured for acceptance. Durability is addressed by specifying certain mixture requirements—for example, the SCM content, cement content, *w/cm*, and air content. For the most part, this approach works, but such specifications cannot be extended to new materials or new requirements (such as specifying a 50-year service life rather than a 20-year service life). Measuring and specifying durability has long been recognized as an area of weakness in the concrete knowledge base. Both topics have been subjects of active research in recent years. Studies and field trials have successfully demonstrated practical testing procedures that can be used to assess durability, including tests for surface resistivity to evaluate resistance to chloride ingress, and the Super Air Meter (SAM) to characterize the air void structure. While further research is certainly needed, the available tools seem adequate technologies for improving the reliability of achieving durable concrete through the use of performance-type specifications. A performance-type specification uses certain quality characteristics indicative of performance to improve current prescriptive specifications as a step toward true performance-related specifications.

For successful implementation, a performance-type specification has to be practical and acceptable to both state DOTs and industry. To be acceptable to DOTs, performance specifications may need to include some prescriptive elements until it can be proven that concrete can be successfully evaluated using only a few performance measures. To be acceptable to concrete producers and contractors, the testing requirements associated with these measures have to be reasonable. To assist in the implementation of performance specifications for concrete paving mixtures, FHWA will be developing guidance documents and training for state DOTs as well as contractors.

Hybrid Specifications Implemented by PANYNJ

The PANYNJ allows concrete mixture proportions to be determined using a performance-based specification that also includes some prescriptive requirements. As an example, for bridge decks, contractors must submit mixture proportions that meet requirements for:

- Compressive strength;
- Charge passed (less than 1000 coulombs using an accelerated 28-day version of ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration"); and
- Maximum shrinkage (no more than 0.03% at 28 days per the dry method specified in ASTM C157/C157M, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete").

Although contractors have some flexibility in designing a mixture to meet these performance requirements, a prescriptive component of the bridge deck specifications requires a maximum *w/cm* of 0.40 and a nominal maximum aggregate size of 1.5 in. (38 mm).

Some might say that this specification is too prescriptive and is not truly performance-based. However, the Port Authority's experience has been that, without the aforementioned requirements, the concrete mixture provided by producers would be inferior to those that have been obtained using these requirements. The Port Authority also has found that there is little interest or incentive for concrete producers to perform the necessary research with their materials to produce more durable concrete. So, while the Port Authority agrees that a pure performance-based specification is a good idea, it also notes that there are very few concrete producers that have the facilities, staff, and interest in bringing such a specification to fruition.

The PANYNJ view is that acceptance criteria that will result in a durable concrete bridge deck with a predicted service life of 100 years when subjected to chloride exposure (typically, Exposure Class C2 for Port Authority projects) are lacking in the concrete industry. The service life prediction is typically based on models that use diffusivity and permeability of concrete as inputs. The results of testing per ASTM C1202 (often called the rapid chloride permeability test [RCPT]) are typically used to determine concrete permeability. A RCPT result of less than 1000 coulombs is generally accepted as low-permeability concrete. While mixtures are typically evaluated using service life prediction models such as Life 365[6] or STADIUM®,[7] these software packages have a major flaw—they are only designed to model transport in uncracked concrete. Significant cracking in a bridge deck subjected to deicing chemicals will reduce its service life compared to predictions by these models. It is worth noting that many consultants and agencies do not perform RCPT evaluations during actual construction, with common reasons being that the test is costly and only a few laboratories can perform it. The Port Authority's experience with this test is that it can be used for quality acceptance, when properly specified, and it is not costly to run. For these reasons, the test is specified for acceptance of concrete on Port Authority projects such as bridge decks, where durability is of primary concern. Historical data on Port Authority projects show instances of concrete with compressive strengths greater than 6000 psi (41 MPa) that failed to meet the RCPT requirements of less than 1000 coulombs. This demonstrates that strength and *w/cm* requirements alone are insufficient for producing low-permeability concrete, particularly when the water content of the concrete is never verified.

The Port Authority also evaluates concrete mixtures during placement using AASHTO T 318, "Standard Method of Test for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying." The water content of fresh concrete is a good indicator of the eventual hardened concrete permeability and drying shrinkage potential, two important properties for predicting and enhancing concrete durability and service life. However, while the test has been shown to be accurate and reproducible when properly done, it is not in common use in the concrete industry.

The Goethals Bridge, a major crossing in the New York City metro area, is now under construction under a Private Public Partnership (3P) contract. In preliminary discussions with the project's consultants and contractors, the Port Authority was disappointed that the model used to predict a service life of 100 years was based on the transport properties of the concrete, but the model ignored the effect of cracking in the deck. Furthermore, there was no acceptance testing recommended during construction to verify that the assumed transport properties of the concrete were being achieved. At the Port Authority's insistence, the deck concrete mixture design required a shrinkage of 0.03% at 28 days, per the dry method in ASTM C157/C157M, and a 1.5 in. nominal maximum aggregate size to minimize cracking potential. RCPT testing was also performed on samples cast from bridge deck concrete delivered to the site to confirm that the assumed transport properties were being achieved.

The concrete industry needs to develop realistic prediction models, concrete mixture proportions, and acceptance criteria for reinforced concrete subjected to chlorides that can more realistically provide a service life of 100 years with minimal maintenance. After these tools are developed, owner agencies such as the Port Authority will be more open to discussions of implementing fully performance-based specifications for durability.

Concrete Industry Perspectives

A 2014 review of project specifications conducted by the National Ready Mixed Concrete Association (NRMCA) revealed the following[8]:

- In 85% of the reviewed specifications, there was a restrictive limit on the maximum quantity of SCMs. There was no associated exposure condition, such as ACI 318 Exposure Class F3 for cyclic freezing and thawing, that would warrant this limit;
- In 73% of the specifications, there was a limit on the maximum *w/cm* of concrete mixtures. Again, there was no associated exposure condition which would warrant this limit;
- In 46% of the specifications, there was a requirement for a minimum cementitious material content. With the exceptions of floor slabs or environmental engineering structures, this is not consistent with ACI standards;
- In 27% of the specifications, additional restrictions, beyond those in the pertinent material specifications, were imposed on the type or characteristics of SCMs that could be used; and
- In 25% of the specifications, requirements were imposed on the combined aggregate grading. This requirement does not exist in ACI standards.

A 2012 industry survey by NRMCA reported that the average SCM content in concrete mixtures was 18% of the total cementitious material content, with fly ash constituting approximately 80% of total SCM usage.[9] Survey respondents indicated that the primary reason for not using higher quantities of SCMs was because of limits prescribed in project specifications. Implementation of performance-based specifications, and the elimination of prescriptive limitations on concrete mixtures, will allow increased use of SCMs. In turn, this will support the development of concrete mixtures better optimized for durability performance, and it will support sustainable construction initiatives. Imposing specification limits for cementitious materials content and *w/cm*, when not required, can result in concrete mixtures that are not optimized for performance and do not support sustainability initiatives. These two requirements also result in compressive strengths that are higher than specified, thus reducing the incentive to improve concrete quality control. Figure 1 illustrates a poor level of quality control (coefficient of variation greater than 11%) in a project with a minimum

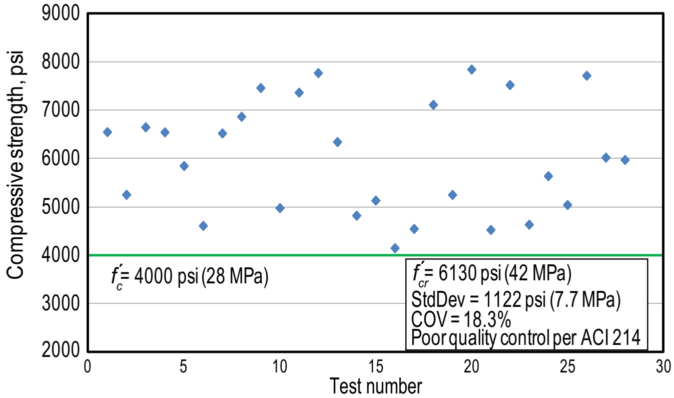

Fig. 1: Variability of compressive strength test results from a project with a specified minimum cementitious materials content requirement (Note: 1 psi = 0.007 MPa)

cementitious materials requirement. An NRMCA study showed that at the same *w/cm*, increasing the cementitious materials content of concrete resulted in higher shrinkage and chloride penetrability at similar strengths.[10]

From an industry perspective, evolution to performance-based specifications for concrete mixtures can occur when:

- The specification writer at a design firm evaluates the firm's current specifications for prescriptive provisions and their purposes relative to a project, eliminates requirements that do not pertain to the project, and proposes performance-based alternatives, if necessary;
- The alternative specification includes basic requirements for concrete in accordance with Chapters 19 and 26 of the ACI 318-14 Building Code and covered in ACI 301-16. The specification should include exposure class for durability, specified strength, and maximum *w/cm* consistent with the exposure class, nominal maximum aggregate size, air content, slump or slump flow, chloride limit, and temperature limits; and
- These performance requirements may include an evaluation of permeability (per ASTM C1202), shrinkage (per ASTM C157/C157M), alkali-silica reactivity (per ASTM C1778, "Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete"), sulfate resistance (ASTM C1012/C1012M, "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution"), as well as a thermal control plan for mass concrete. When performance tests and criteria are included, prescriptive provisions should be removed, as over-specification can result in non-optimized mixtures that will not perform as intended.

Performance-based specifications are being adopted for transportation structures, with good success, by various state highway agencies, including Virginia DOT, Illinois DOT, Washington DOT, Vermont DOT, PANYNJ, and New York DOT. Other resources for the evolution to performance include ACI 329R-14, a report on performance-based requirements,[11] and ACI 211.5R-14, a report on performance-based mixture submittal.[12] The NRMCA has championed the move toward performance-based specifications since 2002. Some of the associated developments include producer quality initiatives, a quality certification program, guide performance specification, guide to improving specifications, a checklist produced in cooperation with the American Society of Concrete Contractors (ASCC), research studies for performance criteria, the Specification-in-Practice (SIP) series, articles, and webinars. Most of these can be accessed from **www.nrmca.org/p2p**.

Performance-based specifications accelerate the adoption of innovation and establish appropriate responsibility for performance. Concrete producers can apply their knowledge of the materials available to optimize mixtures to meet these specifications. Because performance specifications provide the responsibility and incentives to attain better quality, they incentivize the producer to become more technically proficient and to focus on quality. This can result in reduced time and cost expenditures needed to address project problems, and it can lead to greater confidence in concrete construction in general. Given that all project stakeholders will benefit from their implementation, performance-based specifications are the future for the concrete industry.

Challenges of Implementation of Performance-Based Specifications

From the perspective of a practicing consulting engineer, there are three main challenges to practical implementation of a performance-based specification:

- The project team must understand the performance needs in the context of project costs;
- The project team must ensure that the specification can be practically implemented; and
- The specification must address a realistic and efficient quality control testing program.

First, the owner and design engineering team need to have a firm grasp of the performance they need or want relative to the cost of the project. For example, it is not practical for most projects to require concrete to last hundreds or thousands of years when we only have about 100 years of historical data on reinforced concrete (and less with modern cements and SCMs). This requires unrealistic projections of models and test criteria. Project documents must clearly spell out the definition of service life and all related requirements so that all parties are striving for the same goals. It also is necessary to address mechanisms of deterioration other than corrosion of reinforcing steel, such as alkali-aggregate reactions (AAR), cyclic freezing-and-thawing damage, and sulfate attack.

Numerous computer models exist that offer prediction of chloride ingress; rather than leaving software selection as an open issue, designers should identify specific software of their choosing and require it by specification. This is needed because the available software programs have vast differences in model capability, validation testing requirements, and cost. Performance tests are often incorrectly specified in design documents, and some tests may conflict with one another. For example, cracking is often neglected by software models. Unfortunately, development of highly corrosion-resistant concrete mixtures on the basis of uncracked paste properties can lead to autogenous shrinkage and early cracking susceptibility. Care should be taken to select the proper test for the desired performance and remember to address cracking as well, because cracks will short-circuit the service life of a well-designed concrete mixture. Ultimately, the owner and design engineer need to do their homework and be realistic with performance goals and criteria.

Second, the project team needs to ensure that the specification was developed properly with respect to practical issues and implementation. Are the necessary materials available in the local market? Are the local labs equipped to perform the necessary testing? Are the contractors aware of the need to address new requirements in their bids? One effective way to accomplish this is to involve all relevant stakeholders from an early stage in the specification development. Contractors, materials suppliers, and testing labs should be given the opportunity to evaluate and comment on specifications during the development. This will help lead to harmony once the specification is implemented. A recent example of this approach is the Illinois Tollway Authority's implementation of a new high-performance concrete bridge deck specification.[13]

Finally, the implementation of an effective performance specification must include realistic and efficient quality control testing. Overly complex and logistically challenging performance testing will discourage project team members and lead to conflicts or litigation. Whenever possible, preliminary qualification testing should be performed as early as possible and should include surrogate tests that have been validated in the laboratory for a particular mixture. For example, electrical resistivity measurements are often used as a surrogate to diffusion-based transport properties. However, a common mistake is forgetting to perform an initial qualification of the electrical test technique. Electrical properties vary with constituent materials; therefore, a correlation test is always needed (in accordance with ASTM C1202) to a ponding or immersion (true diffusion) based test method. This relationship cannot be assumed without prior test data for correlation. It is also desirable to set forth a resolution protocol for instances in which the quality control performance requirements are not met. Retesting, coring the structure, and application of a coating if retests are not satisfactory, are possible courses of action.

As producers gain experience with performance-based specifications, the challenges posed by acceptance testing may become less imposing. A producer may be able to offer several "off the shelf" mixture options for durability performance that are backed by prior test history. A similar framework is already in place for specification and acceptance for flexural strength properties for pavement concrete. This will not eliminate the need for acceptance testing for each project, but could potentially reduce the extent of acceptance testing required, thereby making performance specifications for durability feasible even for smaller projects.

Framework for Performance-Based "Alternatives" for Specifying Durability

Many of the current specifications and codes (for example, state and local DOTs specifications or ACI 318) are based on empirical observations that relate to aspects of mixture design. For example, the potential for cyclic freezing-and-thawing damage is currently addressed through limits on total air content and *w/cm* requirements. While these empirical approaches are useful, there have been recent developments in the area of performance specifications.[14] Figure 2 illustrates a general approach that can be used to develop performance specifications by relating measured test results (Step 1) to material properties (Step 2). These material properties can then be used in predictive equations to estimate the service life or performance of concrete elements (Step 3). The estimated service life can then be related to performance grades in the specification (Step 4). This approach is powerful in that it allows variations in properties obtained in service to be related to performance based criteria (for example, time in service or cracking potential). Figure 2 also illustrates specific approaches that could be implemented to optimize performance of concrete subject to chloride exposure, cyclic freezing and thawing, or cracking due to restrained shrinkage. The following section provides a brief overview of the approaches used to predict the time to reach limit states associated with corrosion[15] and cyclic freezing and thawing.[16,17] Information regarding cracking due to restrained shrinkage can be found in the literature.[18]

In transport-related forms of degradation such as reinforcing steel corrosion, the penetration of an aggressive species like a chloride ion can be related to a material property that describes the pore structure and connectivity, such as the formation factor. The formation factor, or F Factor, can be related to both a diffusion coefficient[19] and rapid field tests such as electrical resistivity. Reference 14 provides a case study for a bridge deck in Indiana. A sealed 91-day F Factor of 2400 was related to an anticipated 50-year service life. Practical field measurements for use in quality control and material acceptance were related to the indicated F Factor and to a design resistivity on a sealed sample.

Similarly, a sorption-based performance approach has potential for the development of specifications for concrete mixtures that are resistant to cyclic freezing and thawing. Current prescriptive specifications for concrete impose empirically based limits on air content and *w/cm*.[17] The sorption-based approach is based on the degree of saturation of concrete after a short exposure to water (with the gel and capillary pores in the matrix being water filled) and the rate of

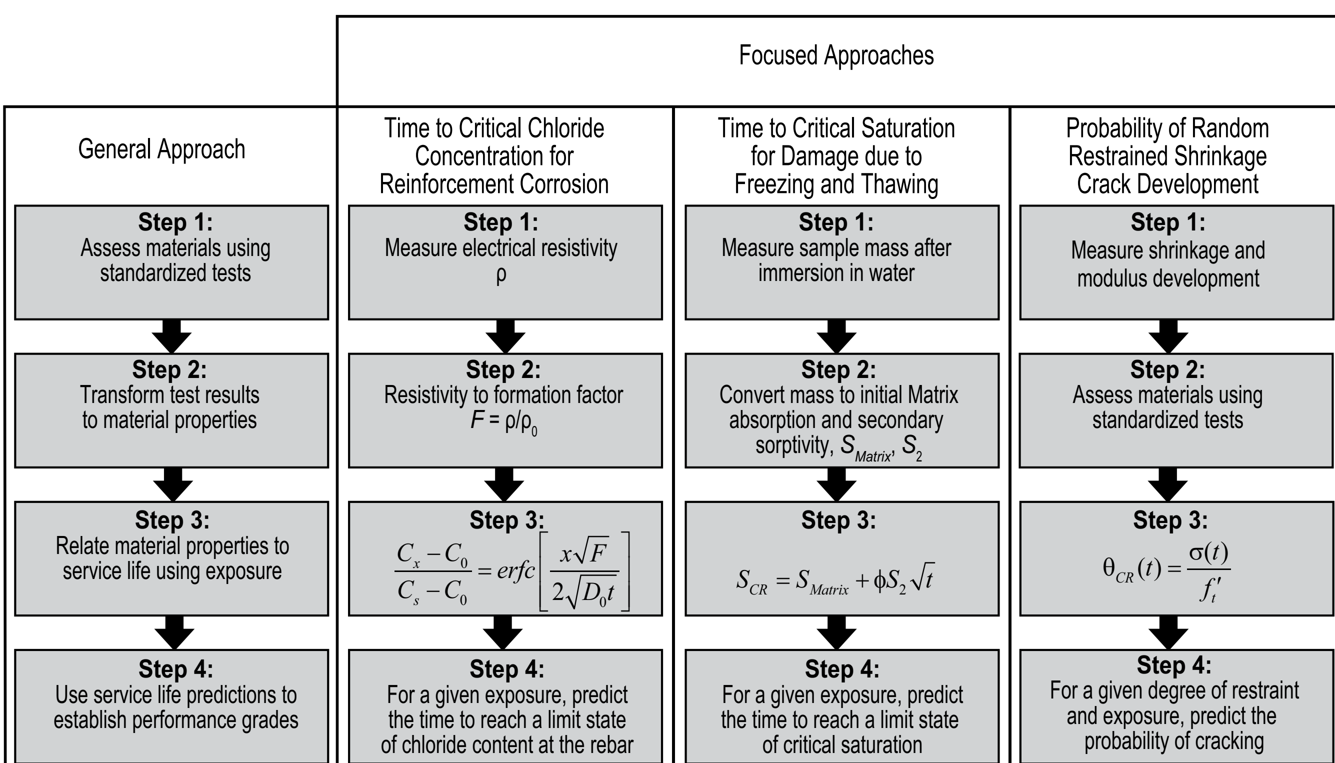

Fig. 2: Performance specifications can be developed by relating test results to material properties used in predictive equations

infilling of the air voids. While a variety of methods exists to ascertain these properties, recent research has shown that simple mass fresh air tests (for example, results of SAM tests) or mass measurements can be used for quality control and material acceptance testing. The performance-based approach could be useful to consider the role of topical treatments (sealers) or water-blocking admixtures.

The approach discussed in this section provides a potential alternative to empirically based prescriptive specifications. While there is no doubt that additional research is needed for the concrete community to become familiar with such approaches, it is important to note that the described approach relates acceptance test results to material properties and anticipated performance. This can be quite powerful in enabling innovations in mixture design, increased use of rapid sensing for quality control and acceptance, and improved strategies for managing the life-cycle of concrete infrastructure elements.

Summary and Looking Forward

The general consensus of the panel was that performance-based specifications have great potential as an alternative to prescriptive specifications. While it is fully expected that prescriptive specifications will remain necessary, performance specifications can provide an alternative that can lead to innovation, potentially more sustainable mixtures, improved concrete quality, and concrete mixtures optimized to meet performance requirements. Opportunities exist for improved laboratory tests that can be used for rapid assessment as well as for predicting long-term field performance. In addition, innovative methods are emerging for implementing rapid and reliable tests for measurement of transport properties. Advances in experimental methods[20,21] and transport modeling are also likely yield software models that are able to better account for the effects of cracking on chloride ingress.[22,23] Yet, the complexity of specifications, acceptance testing, and modeling will need to take into account project size and durability performance needs. For these reasons, performance specifications are suggested as an alternative to prescriptive specifications, rather than a complete replacement.

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Additional information on the ASTM and AASHTO standards discussed in this article is available at **www.astm.org** and **www.transportation.org**, respectively.

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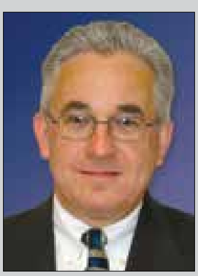

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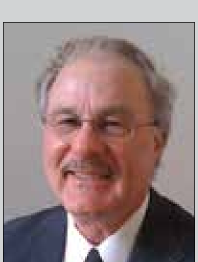

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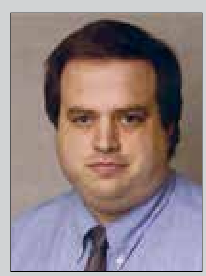

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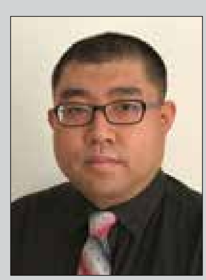

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