On Aggregate Grading

Is good concrete performance dependent on meeting grading limits?

BY KARTHIK H. OBLA AND HAEJIN KIM

Specifying concrete mixtures with well-graded (WG) combined aggregates can be controversial. Advocates[1-4] argue that such mixtures have optimized packing and minimal voids and therefore minimize the cementitious paste required for a given workability. They also claim cost savings, enhanced pumpability and finishability, better resistance to segregation, improved shrinkage properties, reduced temperature-related effects, and greater durability relative to other mixtures. Opponents argue that mixtures with WG combined aggregates don't necessarily lead to optimized performance, but might actually cost more. They also opine that the aggregates available in some regions may make it impossible to comply with a rigid WG combined aggregate specification or may cause handling problems as the aggregates are transferred from the quarry to the concrete plant and to the concrete truck.

Compounding this, published studies show mixed results.[5-13] In an effort to resolve the controversy, we initiated a study at the National Ready Mixed Concrete Association (NRMCA) Research Laboratory in January 2004. Answers were sought to the following questions:

- Does the use of WG combined aggregates lead to improved aggregate packing density?
- Does the use of WG combined aggregates improve concrete performance?

The results are summarized here, but detailed, downloadable research reports[14,15] are available.

AGGREGATE PACKING

For this investigation, we defined a combined aggregate as WG when its grading parameters plotted in Zone II of the coarseness factor (CF) chart[1,3] (Fig. 1) and met the recommended distribution described in ACI 302.1R-04[3] (Fig. 2) that is often referred to as the 8-18 distribution. (Note that the recommended distribution is actually between 8 and 22% retained for the smaller maximum size coarse aggregate used in this study.) If it didn't meet both requirements, we defined a combined aggregate as not well-graded (NWG).

Five WG and five NWG combined aggregates were prepared using material from a single source in Maryland. The WG aggregates were developed by combining different proportions of coarse aggregates (size numbers 57 and 8 per ASTM C33) and fine aggregate by volume. The NWG aggregates were developed by combining different proportions of size number 57 coarse aggregate and fine aggregates. The CF and 8-18 charts for the WG and NWG combined aggregates are plotted in Fig. 1 and 2, respectively.

Combined aggregate void content was determined according to ASTM C29, except that the combined aggregates were blended thoroughly using a scoop (or shovel) (Fig. 3). The test was repeated three or four times with fresh aggregate batches, and the average void content was calculated.

Void content test results are plotted in Fig. 4. WG

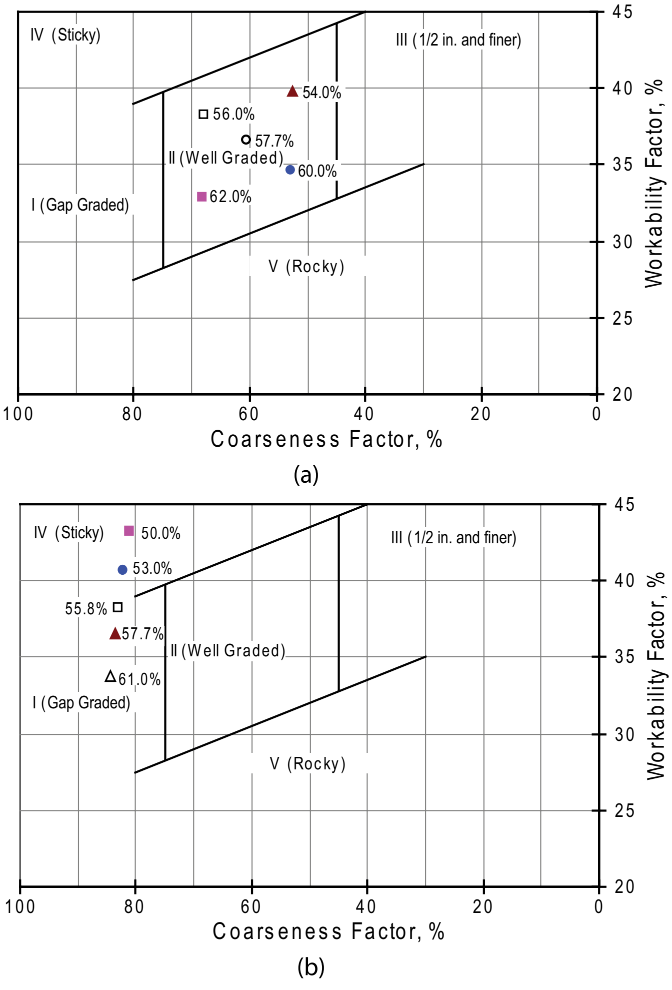


Fig. 1: Coarseness factor charts for aggregates from Maryland: (a) WG combined aggregate; and (b) NWG combined aggregate. Coarseness factor is the weight of the material retained above the 3/8 in. (9.5 mm) sieve divided by the weight of the material retained above the No. 8 (2.36 mm) sieve, expressed as a percent. Workability factor is the weight of the material passing the No. 8 (2.36 mm) sieve divided by the total aggregate weight, expressed as a percent. The value adjacent to each data point is the volume of the coarse aggregate (comprising size numbers 57 and 8 per ASTM C33) divided by the total aggregate volume, expressed as a percent

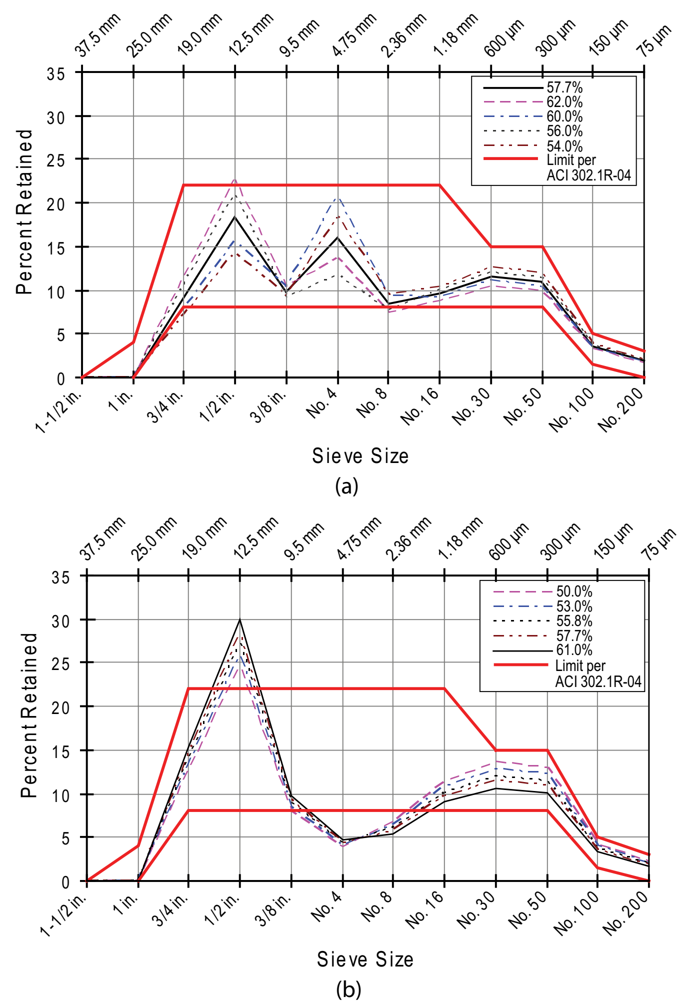


Fig. 2: Material grading charts for aggregates from Maryland: (a) WG combined aggregate; and (b) NWG combined aggregate. The value indicated for each grading is the volume of the coarse aggregate divided by the total aggregate volume, expressed as a percent

aggregates had average void ratios between 23.8% and 26.7%, with an overall average of 25.5%. NWG aggregates had average void ratios between 21.6% and 23.3% with an overall average of 22.5%. So, for this aggregate source, WG aggregates had about 3% higher void content than NWG aggregates. The study was then extended to a round robin program, with aggregates tested in multiple locations around the country.

Round robin program

Participants in the round robin program included:

- Titan America Technical Services, Jacksonville, FL;
- Heidelberg/Lehigh Research Facility, Atlanta, GA; and
- Aggregate Industries, Denver, CO.

The participants conducted basic tests such as specific gravity, absorption, sieve analysis, and dry rodded unit weight and supplied that information to us. We provided the protocol for these tests by suggesting proportions for combined aggregates that were typical for slab-on-ground concrete mixtures. For each participant, we suggested five or six aggregate proportions. At each location, the intermediate coarse aggregate was obtained from the same quarry as the larger coarse aggregate to keep the particle shape consistent and thereby minimize the influences of different particle shapes on test results.

Fig. 3: Void content test sequence: (a) fine and coarse aggregates; (b) blended aggregates; and (c) unit weight test

Void content

Void content test results from the three round robin participants are plotted in Fig. 5. Figure 6 summarizes the void content of the aggregates from the four locations, including Maryland. These data indicate that the void content for combined coarse and fine aggregate isn't necessarily minimized if the aggregates are blended to meet the common recommendations for WG aggregates.

To summarize, for a given aggregate source, WG combined aggregate had almost the same or higher void content as NWG combined aggregate.

CONCRETE PERFORMANCE

We next worked with Titan America Technical Services and Heidelberg/Lehigh Research Facility to investigate the effect of aggregate grading on concrete performance. Our internal study was divided into four stages in which we varied the amounts of cementitious material and used different types and quantities of supplementary cementitious materials and chemical admixtures. The results from our four test stages and the stages from both the collaborating labs are discussed next. In each stage, two or three WG concrete mixtures and two or three NWG concrete mixtures were prepared.

Mixture proportioning and testing

Within each stage, the absolute volumes of cementitious materials, mixing water, and total aggregate were held constant. Different volume ratios of coarse (aggregate size numbers 467, 57, or 67), intermediate (aggregate size number 8 or 89), and fine aggregates were selected to attain multiple WG and NWG mixtures. Figure 7 shows grading charts for the WG and NWG aggregates used in mixtures tested at the Heidelberg/Lehigh Research Facility. For each stage, the first mixture was the control and contained aggregate proportioned according to ACI 211.1,[16] Table 6.3.6 (the control mixture in each stage had NWG aggregates). The other mixtures prepared using NWG aggregates were developed by increasing or decreasing the coarse aggregate content. The mixtures prepared using WG aggregate were developed by adding the intermediate aggregate.

All concrete batches were tested for slump per ASTM C143, air content per ASTM C231, density per ASTM C138, temperature per ASTM C1064, bleeding per ASTM C232 (modified), 28-day compressive strength per ASTM C39, and drying shrinkage per ASTM C157 (with the exception that specimens were moist-cured for 7 days and then stored at 50% relative humidity for 28 days). We also performed column segregation tests (a modified version of ASTM C1610) and finishability tests on specimens in our lab. Details of the nonstandardized tests and deviations from ASTM standards are provided in Reference 15.

Because the mixing water content and admixture dosage was held constant within each stage, we assumed that a higher measured slump for a specific mixture would be indicative of a lower water demand.

Concrete properties

For each stage, performance properties for several mixtures containing WG and NWG aggregates were compared with the control mixture. Shrinkage test results are plotted in Fig. 8. Out of 13 mixtures with WG aggregates, 12 had similar shrinkage values (within the range of testing variability) and one mixture had a higher shrinkage relative to the control mixture. Relative to the control mixture, mixtures with WG combined aggregates exhibited the following results:

- Water demand—about the same in 67% and higher in 33% of the cases;

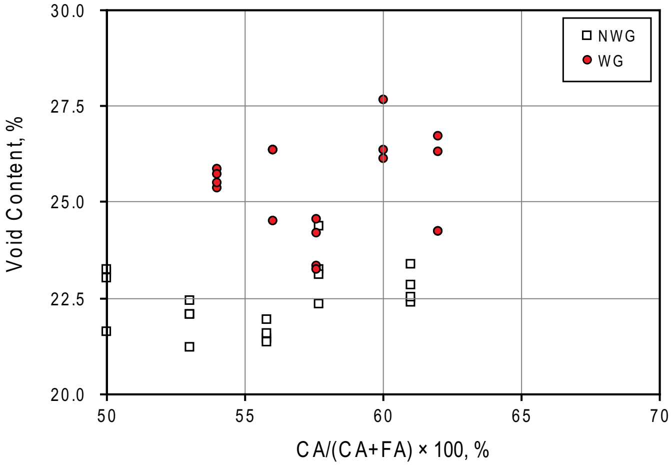


Fig. 4: Void content for WG and NWG combined aggregates from Maryland. CA and FA are the volumes of the coarse and fine aggregates, respectively

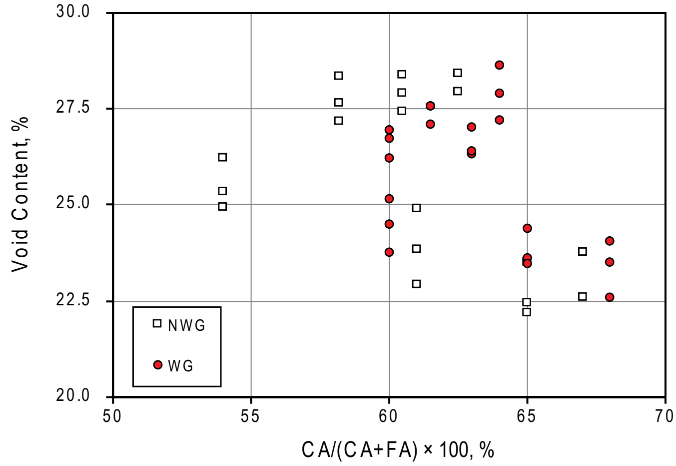


Fig. 5: Void content for WG and NWG combined aggregates from Florida, Georgia, and Colorado. CA and FA are the volumes of the coarse and fine aggregates, respectively

- Bleed water amount—about the same in 75% and higher in 25% of the cases;
- Strength—about the same in 67% and lower in 22% of the cases;
- Shrinkage—about the same in 92% and higher in 8% of the cases;
- Finishability—similar or better, depending on where the WG aggregate was located inside Zone II of the CF chart; and
- Segregation—varied, depending on where the WG aggregate was located inside Zone II of the CF chart.

For the mixtures prepared at three different locations in the country, those designed to meet a WG combined aggregate specification didn't necessarily have lower water demand, lower bleeding, lower shrinkage, or higher strength than the control mixture (with NWG combined aggregates). When mixtures with NWG combined aggregates had higher coarse aggregate contents (5 to 10%) than the control mixture, they tended to have a lower water demand but higher bleeding and segregation. Based on the results, there is no assurance that a concrete specification that includes a requirement for WG combined aggregate through compliance with CF or 8-18 distribution limits will lead to reduced mixing water content or lower shrinkage.

Proportionate properties

We must caution that our observations do not mean that aggregate grading is unimportant for concrete performance. For example, if adequate fine material is not present in a concrete mixture, then the concrete can be prone to segregation and higher bleeding. In contrast, a mixture with excessive fine material can be sticky and difficult to finish. For example, ACI 211.1, Table 6.3.6, recommends that if fine aggregates have a high proportion of fine material (manifested by a low fineness modulus), then the amount of coarse aggregate should be increased, thereby indirectly decreasing the quantity of fine aggregate in the concrete mixture. WG combined aggregate obtained through the use of CF and gradation charts is typically proposed as an improvement over the procedure indicated in ACI 211.1, Table 6.3.6.

While complying with CF and gradation chart limits didn't lead to reductions in water demand or shrinkage in our study, we did find that compliance led to better finishability and lower segregation relative to control mixtures depending on where the WG mixture was located inside Zone II of the CF chart. At a CF of 60% and WF of 35%, it was possible to attain lower segregation but similar finishability, whereas at CF of 68% and WF of 33%, it was possible to attain better finishability but similar or higher segregation. This indicates that the concrete producer could make use of tools such as the CF and grading charts to evaluate whether concrete mixture performance can be optimized using local materials and within production constraints.

Compare

For those interested in conducting similar studies using their local materials, a detailed approach is provided in the appendix of Reference 15. Keeping in mind that comparisons between WG and NWG mixtures must be made with the same general variables, the following points should be noted:

- For all mixtures, the types and amounts of both the cementitious materials and admixtures should be identical;

- The intermediate aggregate should ideally have the same shape and texture as the larger coarse aggregate;
- For both the WG and NWG mixtures, the nominal maximum size of the aggregate should be the same;
- The coarse aggregate content of the control mixture should be prepared according to Table 6.3.6 of ACI 211;
- The control mixture must not be over- or under-sanded; and
- The research program should be conducted in a laboratory setting under controlled conditions.

TARGET PERFORMANCE

There are multiple ways to attain target performance, and using WG combined aggregates as defined by CF and grading charts is one of them. That said, however, it's important to note that CF and gradation should not be invoked as requirements in project specifications. If low shrinkage is important for the application, for example, we recommend that the specification require mixture prequalification. This can be done by verifying length change in accordance with ASTM C157, with typical specification limits ranging from 0.04 to 0.06% following a 7-day moist-cure before a 28-day drying period.

Acknowledgments

We extend our sincere thanks to S. Ben-Barka for helping us conduct the test program at the NRMCA Research Laboratory and C.L. Lobo for his review of our reports. We also thank C. Constantino and J. Cook of Titan America, R. Tate of Heidelberg Technology Center, and D. Imse of Aggregate Industries for participating in the round robin test program.

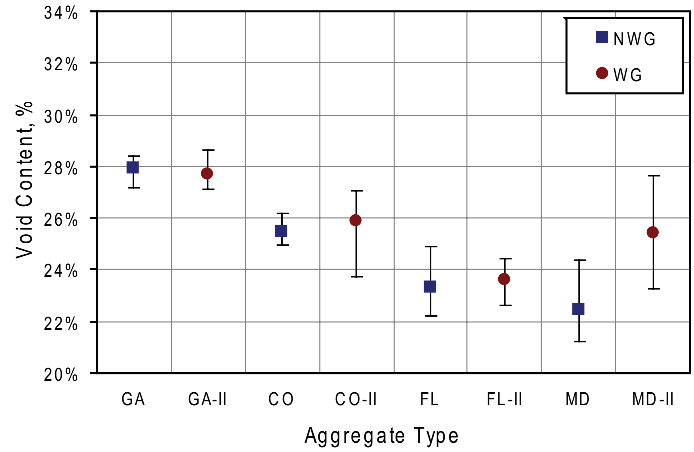


Fig. 6: Void content for WG and NWG combined aggregates from Maryland, Florida, Georgia, and Colorado

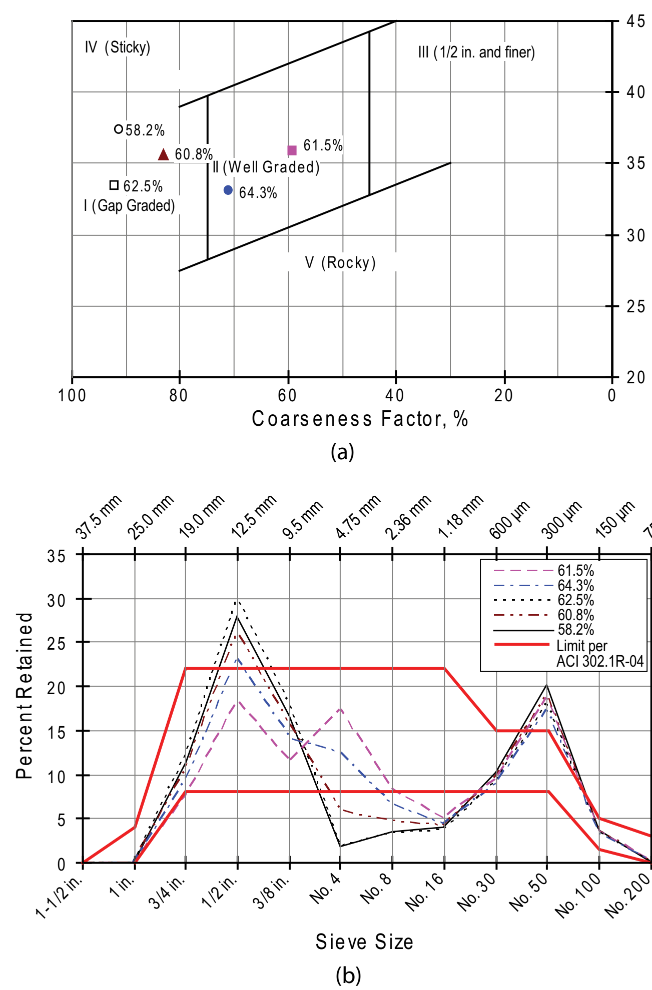


Fig. 7: Grading charts for Georgia aggregates: (a) coarseness factor; and (b) size distribution. The values indicated for each grading are the volume of coarse aggregate divided by the total aggregate volume, expressed as a percent

References

1. Shilstone, Sr., J.M. "Concrete Mixture Optimization," *Concrete International*, V. 12, No. 6, June 1990, pp. 33-39.

2. Harrison, P.J., "For the Ideal Slab-on-Ground Mixture," *Concrete International*, V. 26, No. 3, Mar. 2004, pp. 49-55.

3. ACI Committee 302, "Guide for Concrete Floor and Slab Construction (ACI 302.1R-04)," American Concrete Institute, Farmington Hills, MI, 2004, 77 pp.

4. Phelan, W.S., "Admixtures and Aggregates: Key Elements in 'Athletic Concrete' Revisited," *Concrete International*, V. 26, No. 9, Sept. 2004, pp. 40-43.

5. Cramer, S.M., and Bakke, P.M., "Pilot Study on the Effect of Changes in Total Aggregate Gradation on Portland Cement Concrete Performance," *Final Report*, WI/EP-07-93, Wisconsin Department of Transportation, Madison, WI, 1993, 26 pp.

6. McCall, C.; King, M.E.; and Whisonant, M., "Effects of Aggregate Grading on Drying Shrinkage of Florida Concretes," *Concrete International*, V. 27, No. 3, Mar. 2005, pp. 45-49.

7. Cox, K.P.; Scholer, C.F.; and Cohen, M.D., "An Evaluation of the

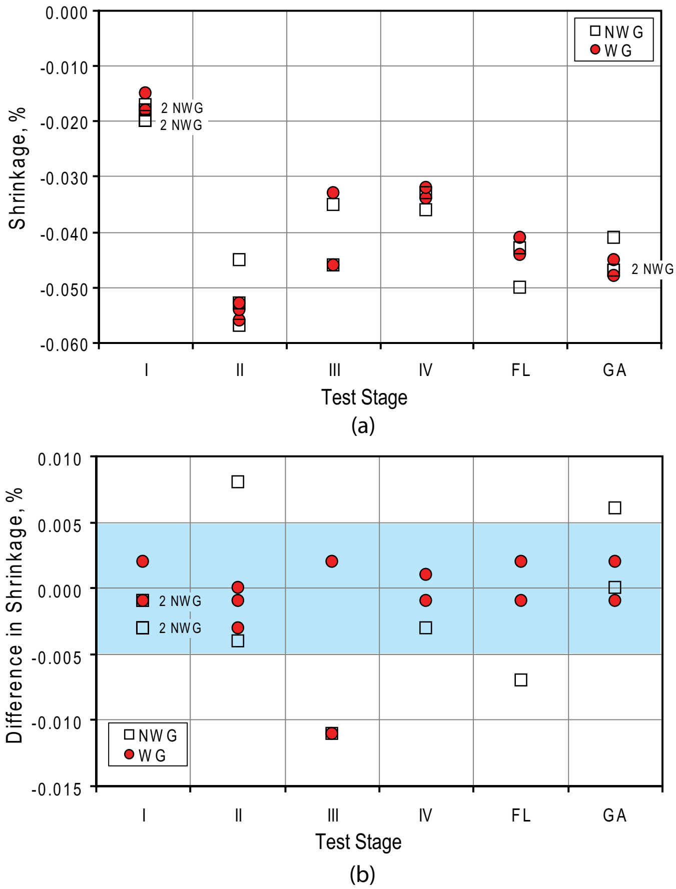


Fig. 8: Shrinkage results for concrete mixtures produced using WG and NWG combined aggregates: (a) total shrinkage; and (b) difference in shrinkage relative to control mixture produced using NWG aggregate. Stages I, II, III, and IV represent the four stages produced at the NRMCA lab; FL and GA represent the stages produced at the Titan America Technical Services lab and Heidelberg/Lehigh Research Facility, respectively

Strategic Highway Research Project Packing Handbook," Purdue University, West Lafayette, IN, 1994, 93 pp.

8. Abrams, D.A., "Design of Concrete Mixtures," Lewis Institute, Structural Materials Research Laboratory, *Bulletin* No. 1, PCA LS001, 1918, 20 pp.

9. Abrams, D.A, and Walker, S., "Quantities of Materials for Concrete," Lewis Institute, Structural Materials Research Laboratory, *Bulletin* No. 9, 1921, 26 pp.

10. Powers, T.C., *Properties of Fresh Concrete*, John Wiley & Sons, Inc., New York, 1968, 664 pp.

11. Dewar, J.D., *Computer Modeling of Concrete Mixtures*, E&FN Spon, London, UK, 1999, 256 pp.

12. Walker, S.W., "Effect of Grading of Gravel and Sand on Voids and Weights," *Circular* 8, National Sand and Gravel Association, Inc., Nov. 1930, 18 pp.

13. Quiroga, P.N., and Fowler, D.W., "The Effects of Aggregates Characteristics on the Performance of Portland Cement Concrete," *Report* ICAR 104-1F, University of Texas at Austin, Austin, TX, 2003, 358 pp.

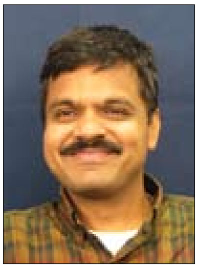
14. Obla, K.; Kim, H.; and Lobo, C., "Effect of Continuous (Well-Graded) Combined Aggregate Grading on Concrete Performance Phase A: Aggregate Voids Content (Packing Density)," National Ready Mixed Concrete Association, Silver Spring, MD, May 2007, 29 pp. (available at www.nrmca.org)

15. Obla, K.; Kim, H.; and Lobo, C., "Effect on Continuous (Well-Graded) Combined Aggregate Grading on Concrete Performance Phase B: Concrete Performance," National Ready Mixed Concrete Association, Silver Spring, MD, May 2007, 42 pp. (available at www.nrmca.org)

16. ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)," American Concrete Institute, Farmington Hills, MI, 1991, 38 pp.

Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors after independent expert evaluation and recommendation.



ACI member **Karthik H. Obla** is the Managing Director, Research and Materials Engineering at the National Ready Mixed Concrete Association, Silver Spring, MD. With 17 years of experience in concrete technology, research, materials, and products, he is an active member of numerous industry technical committees. He is Chair of ASTM Committee C09.49 on Pervious Concrete and Secretary of ACI Committee 232, Fly Ash and Natural Pozzolans in Concrete. He is also a member of ACI Committees 201, Durability of Concrete; 211, Proportioning Concrete Mixtures; 236, Material Science of Concrete; 365, Service Life Prediction; 555, Concrete with Recycled Materials; and C601, New Certification Programs. He received his PhD in civil engineering from the University of Michigan, Ann Arbor, MI, and is a licensed Professional Engineer in Michigan.

ACI member **Haejin Kim** is Manager of the Concrete Research Laboratory at the National Ready Mixed Concrete Association, College Park, MD. He is a member of ACI Committee 211, Proportioning Concrete Mixtures. His research interests include proportioning concrete mixtures, recycling concrete for sustainable development, concrete durability, and the use of mineral and chemical admixtures.