Performance-Based Concrete Mixtures and Specifications for Today

Making the best use of local materials to reduce costs and extend infrastructure serviceability

BY JAMES M. SHILSTONE, SR. AND JAMES M. SHILSTONE, JR.

There are four primary performance objectives for concrete mixtures: 1) strength; 2) constructibility; 3) durability; and 4) architectural appearance. A broad definition of "performance" for construction might be "the efficiency with which a product will accomplish its intended function." During a 1995 workshop,[1] North American concrete leaders agreed that codes and standards are not adequate for durability, and that meeting a strength requirement does not necessarily assure a concrete will be durable in a specific environment. Despite this admonition and due to a method to measure concrete "performance," acceptance continues to be based on strength in general practice.

For performance technology to function, the designer must identify the project performance objective(s), and there must be a means whereby a supplier/contractor can accomplish the task using accepted methods and local materials. Leek, Harper, and Ecob[2] pointed out that, where Codes and Standards of Practice are adequate, the concrete mixture composition may be selected. Since that is possible only for strength, solutions to other objectives must be individually researched. With the millions of possible blends of aggregate types, sizes, and shapes; cementitious materials; and chemical admixtures, this can be an overwhelming, costly task.

The current system is mostly prescriptive and does not address total performance of concrete mixtures. Figure 1 depicts the batching and delivery of concrete. Contract documents limit the qualities of the concrete-making materials to project requirements. They also fix the requirements for the cementitious materials (even quantities, in some cases), total air content, water-cementitious materials ratio, slump, and strength. Based upon those requirements, the contractor selects the proportions at his least cost. Once the mixture proportions are approved, the supplier is required to batch the same proportions regardless of the environmental and materials variations allowed under the broad standards. Performance therefore varies.

From Fig. 1, performance can best be predicted by defining the composition of the mixed concrete that is discharged from the mixer. This process starts with improved methods for selection of proportions, followed by testing, field confirmation, and production quality control to compensate for variations in materials. This approach is not new, as it was described by Abrams[3] and published in other early publications.[4] Though the terms are used interchangeably today, Abrams described the difference between the "mixture design" and the "mixture proportions." The term "mixture design," as used here, describes the desired mixer output in quantifiable, but not quantitative, terms. The supplier/contractor must select the proportions to conform to the design and, through proactive quality control, adjust proportions as

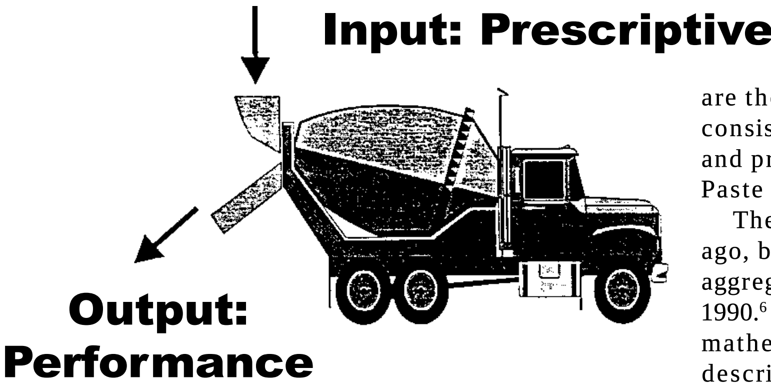

Fig. 1: Concrete—prescriptive vs. performance?

materials vary to consistently produce concrete to meet the intended performance requirement as depicted by the "mixture design."

An aggregate selection method that has evolved over the last 20 years is suggested here. The concept is supported by early, basic technology that evolved from thousands of tests by Duff Abrams and, later, work by C. A. G. Weymouth.[5] After many tests using different methods of proportioning aggregates, Abrams concluded that concrete consists of two segments: 1) aggregate, and 2) paste. That simplifies the problem, since it limits the scope of work by addressing the aggregate as a whole rather than the multiple standard sizes. It also opens the opportunity to make the best use of aggregates that meet quality standards but fail to meet grading standards. Aggregate grading research for soils, base, asphalt, and other applications has proven that the best performance is derived from that blend of equi-dimensional particles that are well-graded from coarsest to finest.

Optimum combined aggregate grading is important for portland cement concrete because it minimizes the need for the all-important second mix component—the paste—and has a significant effect on the air-void structure in the paste. The paste volume should be no more than is necessary to provide lubrication during placement and bind the inert aggregate particles together to resist the forces that will affect the mass during its service life. Abrams reported that water was the most important ingredient in concrete. Even early PCA publications referred to the "Water-Ratio Theory"[4] years before the "Water-Cement Ratio Law" was accepted. The cementitious materials are added to provide lubrication and produce strength when hydrated. Admixtures are the modern "tools" added to the paste to extend consistency, reduce permeability, minimize shrinkage, and provide many other features desirable to a mixture. Paste composition is widely reported by others.

The seeMIX software program, issued over 15 years ago, brought the current attention to the subject of aggregate grading. The background was published in 1990.[6] That program helps users select trial proportions, mathematically "mixes" the concrete, and graphically describes the characteristics of the combined aggregates and paste. We, and other program users, soon learned to identify potential mixture performance based upon the mixture report and graphics. Gap grading (especially at the No. 4 and 8 sieves) and excessive fine sand and cementitious materials content were found to cause problems. Corrections to fill gaps in the aggregate grading led to significant reductions in water, improvements in mobility and finishability, and increases in strength.

Weymouth and Powers[7] (see *Properties of Fresh Concrete*, Fig. 6.1, p. 257) provided helpful insight on segregation due to the relationship between the percent of all aggregate retained on the No. 8 sieve, which is also retained on the 3/8-in. (10 mm) sieve; hence the importance of the No. 4 and 8 sieves. By following these principles and field experience, Lafrenze[8] resolved U.S. Air Force paving problems. Other agencies and concrete suppliers began applying the new technology to improve concrete quality. Efforts to set combined aggregate grading limits to better control mix input have had limited success. In some cases, the results have contributed to costly, wasteful use of local resources.

We have collected and graphically analyzed mix data used for concrete construction for everything from paving to high-rise pumping. The aggregates used in the study were equidimensional crushed stone, natural gravel, and sand. All mixture proportions have been selected to make best use of *local* materials. From these data, we have developed a model performance-based "mixture design" that will satisfy the needs of the vast majority of normal-strength concrete cast in the United States. There's a clear conclusion: A good mixture is a good mixture almost regardless of construction method or service requirement. A copy of the mixture design is appended for your review and testing with your materials. Quality control is important. As materials vary, proportions should be adjusted to fall within the limits shown on the design.

TABLE 1:
MIXTURE DESIGN (EQUIDIMENSIONAL AGGREGATES)

Materials requirements: Portland cement = ASTM C 150 Type I/II; fly ash = ASTM C 618, Class F; aggregate = ASTM C 33 w/blend sizes; nominal maximum size = 1 in.; admixture = ASTM C 494, Type A or D; Air-entraining admixture = ASTM C 260.

Mixture requirements: Max. *w/cm* ratio = 0.50; air content = 5 ± 1.5%; compressive strength at 28 days = 4000 psi or flexural strength = 650 psi; combined aggregate = as shown on the Coarseness Factor Chart with a tolerance of the limits of the trapezoid around the design location; aggregate grading variations = follow the trend on the 0.45 Power Grading Chart without major deviations.

Quality control: Maintain a continuing quality control program, including aggregate testing, and making adjustments in proportions where required to meet the mixture design requirements.

Note to specifier: Adjust the above, including references, to meet project needs. Adjustments in the graphics will be needed only where local aggregate particle availability and/or shapes dictate.

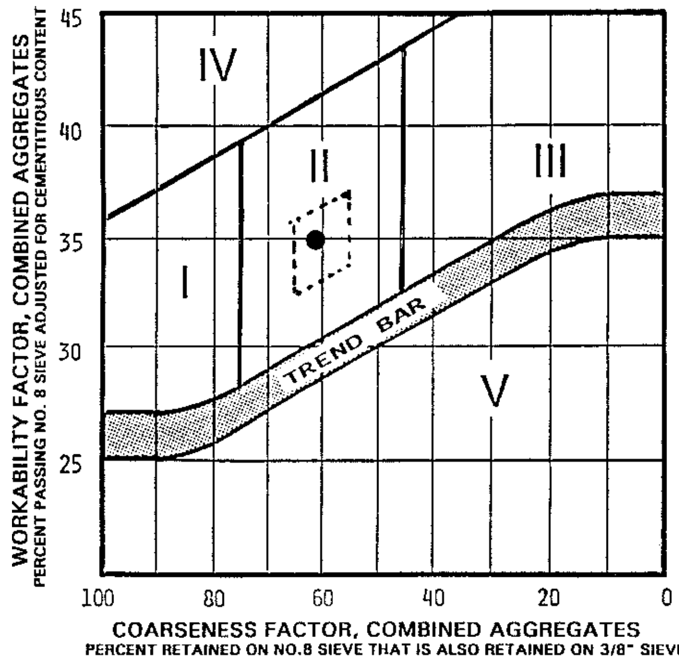

Fig. 2: Concrete mixture design combined aggregate relationships

The mixture design

Table 1, Mixture design (equidimensional aggregates), identifies the mixture and prescriptive requirements for materials, strength, and air content. Figure 2 depicts the concrete mixture design combined aggregates relationships. In regard to the coarseness factor chart, the X-axis is the percent of the combined aggregate retained on the No. 8 sieve that is also retained on the 3/8-in. sieve, and the Y-axis is the percent of the combined aggregate that passes the No. 8 sieve. The term "workability" does not correlate with slump. The research that led to this chart[5] was based on six U.S. bags of cement (564 lb/yd^3 or 335 kg/m^3). A change of one 94-lb (43 kg) U.S. bag of cement necessitates a change of 2.5 percentage points on the Y-axis—added or subtracted. The diagonal bar is the Trend Bar that divides sandy from rocky mixtures. Zone I mixtures segregate during placement. Zone II is the desirable zone. Zone III is an extension of Zone II for 0.5-in. (13 mm) and finer aggregate. Zone IV has too much fine mortar and can be expected to crack, produce low strength, and segregate during vibration. Zone V is too rocky.

Figure828282 3 shows the asphalt industry's 0.45 power grading chart. It is like a semi-log sheet, except the spacing is based on the sieve opening in microns to the 0.45 power. The line representing the percent passing each sieve should not have major dips and rises. While it is preferable to dip below the mix trend line at the No. 8 sieve and finer, this is seldom possible due to the use of fine sand in the U.S. The mix trend line is the product of the mix and not a line from the nominal maximum aggregate size to 0-0.

Figure 4 shows the percentage of aggregate retained on each sieve. It more accurately defines peaks and valleys in the grading. Deficiencies in particles retained on the No. 4 and 8 sieves reflect major problems, and the mixes generally fall in Zone I. It is poor practice to select proportions based upon maximum and minimum amounts, such as 18-8, on a sieve. Three consecutive points in a valley can signify problem mixtures.

Each individual or organization reading this article is invited to test what is reported here to verify its performance using their local materials. Do not depend solely upon standard aggregates. Often, the intermediate particles (No. 4 and 8) are underutilized because they would produce a fine aggregate that is too coarse. ASTM C 33 provides gradings for sizes 89 and 9 to serve

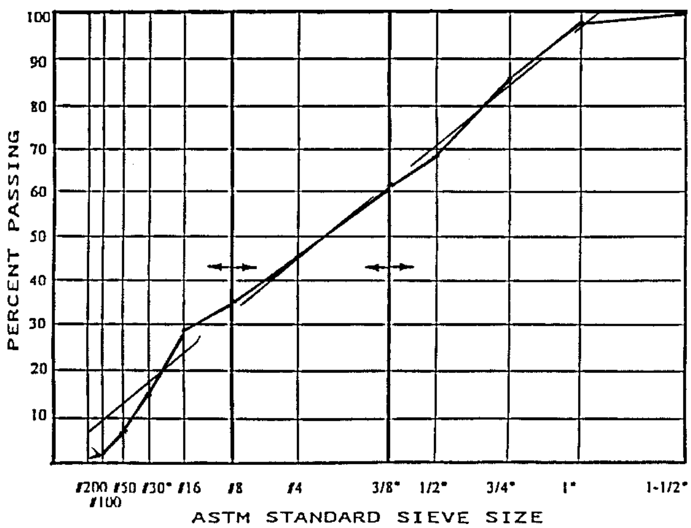

Fig. 3: 0.45 power grading

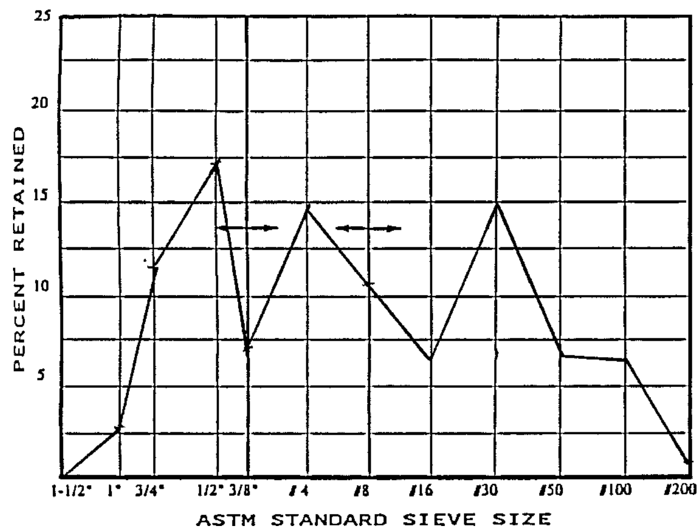

Fig. 4: Percent aggregate retained in each sieve

as blending sizes but, more often, such terms as "buckshot," "bird's eye," "torpedo," "squeegee," "4x8s," and "snow sand" better identify what is available to meet the needs. Some asphalt aggregates and block sand provide the desired particle sizes. Most mix problems are primarily the result of poor (too fine) sand grading. The fine sand affects the water and cement and water is the key to quality.[3]

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Selected for reader interest by the editors.

FACI **James M. Shilstone, Sr.,** is a member of ACI Committees 211, Proportioning Concrete Mixtures; 301, Specifications for Concrete; 309, Consolidation of Concrete; 325, Concrete Pavements; and the TAC High-Performance Concrete Committee.

FACI **James M. Shilstone, Jr.,** is a member of ACI Committees 118, Use of Computers; 214, Evaluation of Results of Tests Used to Determine Strength; 235, Knowledge-Based Systems and Mathematical Modeling for Materials; 303, Architectural Cast-in-Place Concrete; and 304, Measuring, Mixing, Transporting, and Placing Concrete. He is also a member of the Educational Activities Committee; E 705, Educational Computer Activities; the Internet Advisory Committee; and the Membership Committee.