Design Globally, Proportion Locally

by Kevin A. MacDonald, PhD, PE, and Mark Lukkarila

Proportioning shotcrete mixtures requires an understanding of the properties of the constituent aggregate, cementitious materials and admixtures, their interaction, as well as the performance of the shotcrete as an entity itself. It is very important to recall that once it is shot, shotcrete is concrete. It behaves like other types of concrete, and knowledge of the relevant properties of any type of concrete can be used in the design of shotcrete mixtures.

Proportioning and design of mixtures are terms that are used interchangeably. However, the activities involving the two are different. Mixture design involves setting the criteria for the performance of the shotcrete, or other concrete material, while proportioning involves utilizing available materials to meet the design requirements.

Prior to the work of Duff Abrams, there was a recognition that aggregate gradation, among other things, was important in achieving concrete with desirable properties. After adoption of the water-cement ratio (*w/c*) concept, many decades of ignoring the aggregate followed, as it was believed that only *w/c* dictated important properties. As performance expectations of concrete have grown, a rediscovery of the importance of aggregate gradation, surface texture, and particle shape in the overall properties of hardened materials has become widespread. Proportioning of shotcrete mixtures is no exception.

SPEC MIX®, Inc., through its licensees, has been faced with an interesting challenge in this regard—to make shotcretes with the same design properties, using locally available aggregates, as well as locally available cements.

The method employed to achieve this ambitious goal was to design mixtures using a given set of aggregates and then to mathematically describe the properties of aggregates locally available to the licensees to manufacture shotcretes with the same properties.

The initial design of the mixtures involves the years of Fuller's maximum dry density curve, similar to the 0.45 power curve developed by the Federal Highway Administration (FHWA) and used by asphalt mixture designers throughout North America.

The concept behind both of these curves is that gradations lying upon these curves will pack with a minimum void content, resulting in an aggregate-dense material. The equations follow:

Fuller's Curve

$$\%Retained = 100\left(1 - \left[\frac{d}{D}\right]^{0.5}\right)$$

FHWA 0.45 Power Curve

$$\%Retained = 100\left(1 - \left[\frac{d}{D}\right]^{0.45}\right)$$

Where *d* is the individual sieve size and *D* is the maximum size.

These curves can be used in the proportioning of shotcrete and conventional concrete to optimize the use of the paste component by minimizing the amount voids between the aggregates.

Using the gradation bands given in ACI 506, and the maximum packing density concept, trial mixtures were produced and shot. The resulting relevant concrete properties were determined including compressive strength, rapid chloride ion permeability, degree of rebound, and ease of surface finishing. Mixture design information was then based on those mixture proportions that gave the acceptable values for these properties.

In addition to technical evaluation, an economic evaluation was made regarding the cost/benefit of the use of various polymer admixtures, air-entraining admixture, and pozzolans.

Once the designs were complete, a method was developed that would allow other aggregates to be used and would still result in shotcrete with the same properties.

Variations in materials can be significant between two locations within a single state or province. Some manufacturers get around this by manufacturing and shipping from only one or two plants. SPEC MIX®, Inc.'s methods of mixture proportioning allows for these regional variations in construction materials.

The adopted method uses a modified specific surface, including modifications for particle shape, cement gradation, and air content. The method is used by Cemstone Products Company in Minnesota and Wisconsin, for a similar purpose in ready-mix operations. It is similar to that detailed by Ken Day and forms a basis of the Conad system.

Some modifications were required, of course, for shotcrete, including accounting for a wider

range of properties that would normally be encountered in ready-mix concrete. The system has been seen to work very well, however.

An example of the differences in aggregate typically encountered in different areas is shown in Fig. 1 at right. The top example is an angular material, and the bottom is a rounded, natural gravel. Both have a similar gradation. Simply relying on gradation could lead to major problems.

This mixture proportioning method recognizes a rediscovered fact. Aggregate is not an inert filler. Rather, it is all "ert" in the words of Bryant Mather, and its properties can be as important as those of the cementitious materials.

An interesting observation is that meeting a gradation, either in ACI 506 or in project specifications, may not necessarily result in the best quality shotcrete. Gradation is only one important property of the aggregates. It is our experience that the specific surface, or a modification thereof, is more significant than simply meeting a gradation.

In addition, it is important that the suppliers of aggregate understand that once they have submitted a gradation, it is not enough to merely stay within the ACI 506, ASTM C 33, or similarly specified ranges. Rather, the aggregate should be treated as a job mixture formula, as used in the asphalt industry. A job mixture formula allows a very small range of movement, typically 3 or 4% on each individual sieve. This is in recognition that even though you are inside the design bands, a change larger than this is a significant change in proportion, which can result in changes in the properties of the resulting concrete. It is our experience that a similar change in properties can occur in both hardened and plastic properties.

A combination of an understanding of the active contribution of aggregates in the properties of the shotcrete they are part of and in a mathematical model that attempts to describe those relevant properties, results in a mixture proportioning methodology that can accommodate different materials to meet performance requirements of the same design.

Figure 1

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