The Progression of High Strength Concrete

By Kevin A. MacDonald, FACI

The definition of high strength concrete continues to change. This change occurs as the art of achieving a particular strength is reduced to practice, and the structural requirements push at the edge with needs for higher strength. One such example is the CN Tower in Toronto, with its required strength in 1976 of 5000 psi. At that time, this was difficult to achieve. Today 5000 psi concrete is routinely used and produced without special precautions.

In the manufacturing of high strength concrete, there are significant differences from those seen in practice just a few years ago. Cementitious components and content, admixtures aggregates and curing have changed. Once the province of high cement contents and silica fume, much of the developments over the last decade have revolved around a better understanding of, and attention paid to, the microstructure of the concrete. High strength concrete can be modeled as a three phase system – the paste, the aggregate and the interface between them (*Figures 1* and *2*). By taking this approach, an engineered composite material can be designed.

Actions taken to modify the interfacial transition zone between the aggregate and paste have increased the load transfer between the paste and aggregate; thereby increasing the strength of the concrete. It is the action of meta-kaolin, silica fume and other finely divided materials in modifying this interfacial transition zone that originally led to significant increases in strength. These materials were once used at high replacement levels, frequently greater than 10%. While high strength was often achieved, the workability and susceptibility to fracture of the concrete were problems that ultimately limited the strength.

In modern high strength concrete, blends of smaller quantities and fractions of silica fume result in large increases in strength without compromising the ability of the mixtures to be placed. In many cases, ternary or even quaternary blends of pozzolanic material with Portland cement are seen in practice.

One of the reasons for these blends is that the heat generated during the hydration process can cause residual stress within the paste, and reduce the strength of the concrete. While these types of effects can readily be removed in metals by annealing, no such process is available for concrete. The curing process must be engineered to control the hydration reaction so residual stresses are minimized. Temperature monitoring or other devices are used to track the progress and monitor the reaction that produces the binder.

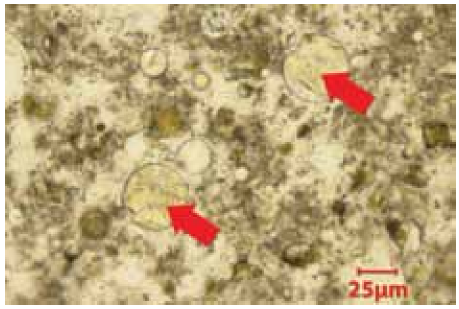

Figure 1: Thin section of concrete showing microstructure of paste. Red arrows are typical flyash particles.

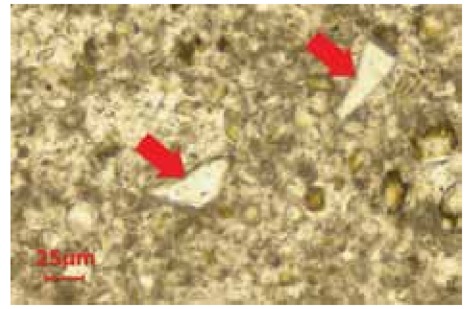

Figure 2: Thin section of concrete showing microstructure of paste. Note the relatively low degree of hydration of the slag particles (red arrows).

The literature at the turn of the 20th century often referred to the curing process as annealing. While having very little to do with the concept of heat treating of metals, this curing, when performed properly, is a critical factor in the performance of higher strength concrete. Strengths up to 20,000 psi have been realized using pozzolanic materials, dispersants, limestone modified cements and careful attention to aggregate materials selection. The limestone acts to nucleate the reaction and reduces the quantity of unhydrated-cement.

Admixture technology has progressed. Stabilizing admixtures and dispersants with a low affinity for the solid surface, where a large fraction of dispersant remains in solution, has allowed mixtures to be held in a state of "suspended animation" while the concrete is placed. They can perform predictably, allowing scheduling of the construction process. Retarders, dispersants and stabilizers will increase the strength.

One of the difficulties that the designer of high strength concrete mixtures encounters is the ability to have workable concrete with very low water/cement ratios. Use of modern high-efficiency dispersants (super plasticizers) has led to observed autogeneous drying of materials due to hydration or vaporation due to high temperature. As a consequence, some very low water/cement ratio concrete have shown good performance in the laboratory but poor performance in the larger structural members, where the heat of hydration is not as readily dissipated and where the sample is not immersed in water for 28 or even 56 days. These limits are advancing by innovations such as the use of lightweight aggregate for internal curing and steel whiskers to distribute stresses.

Aggregate materials are no different. As the paste strength increases, and the interfacial transition zone densifies, the strength of the aggregate or the presence of fractures therein become a limiting factor. Reducing the maximum particle size and carefully selecting the geological origin of the materials can lead to significant improvements in strength.

Recognition by the design and construction team that the concrete strength does not need to be achieved at seven or 28 or even 56 days, but only as the structure is loaded, allows mixtures that have relatively low cement contents and very high pozzolanic replacement to achieve compressive strengths in excess of 15,000 psi.

Care must be taken in the production of high strength concrete in order to ensure that the performance of the concrete in situ is what was intended in the design. Raw materials, batching and handling at the plant and at the installation site must be controlled. Without an understanding of the importance of high strength concrete at the production plant and by the individual vehicle drivers, it will be more difficult to achieve performance of the structure.▪

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