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HIGH-PERFORMANCE CONCRETES - BEHAVIOR OF FRESH CONCRETE

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ABSTRACT

Most of the research in High-Performance Concretes (HPC) since the publication of the State-of-the-Art Report in 1990 has concentrated on increasing basic knowledge regarding HPC performance and properties rather than developing new types of HPC. The behavior of fresh High-Performance Concretes (HPC) concrete is not substantially different from conventional concrete.

1. INTRODUCTION

While many HPC's exhibit rapid stiffening and early strength gain, others may have long set times and low early strength. Since setting and slump loss are not necessarily related, the specifics of each mixture must be analyzed individually. Workability is normally better than conventional concretes produced from the same set of raw materials, at least initially, and super-workable concretes can be used for difficult concrete placements where internal vibration is problematic. Curing is not fundamentally different for HPC than for conventional concretes, although many HPC's with good early strength characteristics may be less sensitive to curing.

However, the high volume of cementitious material and low bleeding characteristics of HPC's, particularly when combined with rapid slump loss, contribute to several characteristics which must be anticipated. Hard troweled surfaces may be difficult to attain in some cases. Plastic shrinkage problems may be exacerbated. While pumping is typically easy with HPC, breakdowns in pump operations may be more problematic. With adequate planning, these characteristics should pose no particular problem.

2 WORKABILITY

The workability of HPC is normally good, even at low slumps, and HPC concrete typically pumps very well, due to the ample volume of cementitious material and the presence of chemical admixtures, particularly HRWR. Page [1990] reviewed pumping operations and concrete mixtures used to successfully pump concrete on the 79 story South Wacker Tower in Chicago. One concern with pumping any concrete, including many of the HSC's is the development of a contingency plan for pump breakdown. Options include multiple pumps so that if one breaks down, concreting operations can be concentrated on one pump until resumption of pumping by all units.

While many HSC's respond well to pumping, once the movement of the concrete and vibration of the pump have stopped, it can be difficult to restart pumping operations due to the thixotropic behavior of these mixes. Contingency plans should therefore also address the issues of line clean-out and disposal of waste concrete. Again, detailed pre-construction and pre-pour meetings are very important.

The influence of internal vibration on air contents was investigated by Simon et al. [1992]. They concluded that air content at the point of insertion was dramatically changed but that away from the vibrator, the effect was minimal. HPC mixes have not been investigated in any depth in this respect but, due to the increase in consistency, should behave as well or better. Cursory examination of cores from C-205 HPC field placement in North Carolina using a bridge deck type of slip form paver with significant internal vibration showed no dramatic difference between cores and standard cylinders.

Hard, smooth, hand troweled finishes may be difficult to attain with some HSC's, with rapid slump loss and somewhat extended set times.

The proper time to begin troweling operations can be difficult to judge. As moisture evaporates from the surface without being replaced, the surface will stiffen and appear ready for troweling. Since the concrete has not achieved true set, however, troweling may produce irregularities in the surface in addition to trowel marks. In addition, the slab must be adequately protected from plastic shrinkage during this time, otherwise severe plastic shrinkage cracks can develop. This is, of course, not a problem for most formed members.

The development of super-workable concretes has already been noted in Chapter 2. These concretes have the ability to fill heavily reinforced sections without internal or external vibration, without segregation and without developing large sized voids. These mixtures are intended to be self-leveling and the rate of flow is an important factor in determining the rate of production and placement schedule. It is also a useful tool in assessing the quality of the mixture. See section 3.5 for a further discussion of test methods. Flowing concrete is, of course, not required in all HPC and adequate workability is normally not difficult to attain.

3 SETTING TIME

Setting time can vary dramatically depending on the application and the presence of set modifying admixtures and percentage of the paste composed of portland cement. Concretes for applications with early strength requirements and concretes containing one of the many non-retarding HRWR's can lead to mixtures with rapid slump loss and reduced working time. This is particularly true in warmer construction periods and when the concrete temperature has been kept high to promote rapid strength gain.

Field trials using HPC intended for early strength applications in bridge decks or other transportation structures were conducted by SHRP C-205 and C-206. The concrete was easy to place, as long as the ready-mixed concrete trucks had adequate mixing capacity. The concrete was also easy to finish with bullfloat or highway straightedge, even though it was somewhat sticky. The early strength development of these mixes was enhanced by keeping the temperature near the maximum permitted by most specifications and then insulating the slabs after placement. This clearly also reduced setting times.

As noted in Chapter 2, the use of large quantities of HRWR or other water reducing admixtures can significantly extend setting times and therefore reduce very early strengths even though strengths at more than 24 hours may be relatively high. Dosage has to be monitored closely with mixtures containing substantial quantities of mineral admixtures so as to not overdose the portland cement if adding the chemical admixture on the basis of total cementitious material. The use of non-chloride accelerating admixtures was employed in mixtures tested by SHRP C-205 investigators [Zia et al. 1993a, 1993b, 1993c] to offset the retarding effects of the minimal dosages of melamine HRWR used. Extended set times are of value when using HPC which does not require very early strength, especially when transit and discharge times exceed about 30 minutes. This is easily attained through the use of retarding admixtures.

4 CURING

Since the last State-of-the-Art Report on High Performance Concrete, significant additional work has been conducted on early age characteristics and on curing requirements or sensitivity of low W/CM ratio concretes with various admixtures. Samarai et al. [1992], examined the influence of temperature, relative humidity and curing in hot climates on HSC properties. They report that the compressive strength of HSC is less sensitive to temperature and relative humidity than conventional strength concrete. However, tensile strength of HSC was found to be more sensitive. Swamy and Bouikni [1990] report that concrete containing very large quantities of ground granulated blast furnace slag require longer moist curing times to develop adequate strength and is more sensitive to drying than plain portland cement concretes, although the concrete used in the investigation was only marginally HPC.

Mak and Lu [1994] investigated HPC which contained GGBFS under non-standard curing conditions, including the effects of temperature rise due to heat of hydration. They found that lack of moist curing, such as might be found in actual, large section members, significantly reduced the compressive strength of concrete in which as much as 50% or more of the portland cement had been replaced by GGBFS, but that a mix with 30% replacement did not have a significant effect. However, they also noted that the reduction in heat of hydration of such high GGBFS mixes, with the associated reduction in microcracking, appeared to offset the extra sensitivity of the mixes to moist curing so that the results were comparable up to 91 days.

The higher initial curing temperatures associated with HPC with high cement contents require that slabs and pavements be sawed earlier than usual to prevent cracking. Cracks which form in the first 24 hours after placement have occasionally been mislabeled as shrinkage cracks. At these ages the concrete is too young to have undergone any significant drying shrinkage.

The higher internal temperatures frequently found with high early strength HPC can create a relatively large temperature change as the concrete cools. For concrete placed during the day and intended for use under early opening to traffic conditions, the temperature drop associated with a drop in the rate of reaction can coincide with cooling temperatures as evening approaches. As the concrete tries to contract, restraint by the base course creates tensile stresses.

A rapid strength gain in concrete is accompanied by a consequent gain in elastic modulus, although typically at a slightly slower rate. The large temperature change occurring with a stiffer concrete will create higher stresses and can cause more pronounced cracking than with conventional concrete pavements unless relieved by sawing. These cracks will occur, regardless of the method of curing, due to stress caused by temperature gradients, but can be minimized if the pavement is insulated on the surface until sawed.

The problem can be exacerbated with concrete mixtures containing large dosages of retarding admixtures. Although retarders, including extended set high range water reducers, delay setting and, typically, the onset of strength gain, increase in the temperature rise compared to non-retarded mixtures is common.

The increase in early strength associated with higher temperatures was not found to be problematic in 20 cm (8 in.) slabs by the SHRP C-205 research team [Leming et al. 1993; Schemmel and Leming 1993], using concretes with high cement factors. Burg and Ost [1992], and Cook et al. [1992], provide additional information on the effects of temperature rise on mechanical properties of HSC in large sections. They conclude that temperature rise is not a significant problem for members where HSC is appropriate. Sanvik and Gjorv [1992] draw the same conclusion for lightweight HSC. Detwiler et al. [1994], and Dhir et al. [1993] found that the use of fly ash in the concrete mixture also improved the resistance to chloride ion penetration of concrete at elevated temperatures. Silica fume was also reported to improve the resistance. Marzouk and Hussein [1990] reported on HPC properties at low temperatures. As expected, strength gain was slowed as temperature dropped. HPC did not appear to be significantly different from conventional concrete.

Early strength gain for transportation applications under field conditions has been reported by Schemmel et al. [1993], Leming et al. [1993], and Whiting et al. [1994]. The results of these field trials indicate that it is possible to reliably produce concretes which attain compressive strengths of 14 MPa (2,000 psi) at 4 hours up to 35 MPa (5,000 psi) at 24 hours, depending on mix composition, under summer and fall placing conditions.

5 TESTING

Tests to measure the workability, resistance to segregation, self-leveling capability and filling capacity of super-workable concretes are not well established. However, substantial research has been conducted in this area. Super-workable concrete mixtures are self-leveling, making the slump test inappropriate. Test methods used by Kuroiwa et al. [1993] to determine the workability of super-workable concrete include the conventional slump cone test, measuring the increase in the diameter of the concrete base, or "slump flow", rather than the reduction in height of the settled concrete, for comparison. A measure of the rheological characteristics based on the rate of increase in diameter during the slump test, termed "flow speed", is also used for comparison. This is determined as the time, in seconds, required for the base diameter to exceed 50 cm (20 in.) [Kuroiwa et al. 1993]. Workability may also be gauged by time of flow through a funnel, similar to standard grout flow cone tests, adapted for use with concrete.

The test method used to evaluate resistance to both segregation and self-compaction simultaneously, termed "filling capacity", involved letting concrete flow down through one branch of a U-shaped tube, under a very slight pressure, and back up the other branch, past a mat of reinforcing bars. The height to which the concrete rose was used as a measure of the filling capacity of the mixture. Other tests include the use of mock-ups. Investigation may include examination of cores for indications of segregation.

Poor filling capacity was noted with some highly workable concrete due to segregation of the paste and aggregate. Filling capacity was found to be reasonably well correlated with the behavior of the concrete in the funnel test, in that concretes which segregated blocked the outlet of the funnel with aggregate, resulting in a longer flow-out time. This phenomenon is, of course, familiar to anyone who has tried to pump concrete which was too "wet" through several elbows.

Considerable research on the effects of different testing parameters of HSC was reported in the previous State-of-the-Art Report. Valuable additional research in this area has been provided by Carino et al. [1994], who concluded that cylinder size, cylinder end preparation, load rate, and testing machine capacity all had significant effects and all had significant interactions. Lessard et al. [1993] also report on the effects of testing methodologies for HSC. While the magnitude of the effects vary from researcher to researcher, the primary conclusions have not. The average measured strength of small cylinders is greater than that of large cylinders, stiffer machines typically provide higher measured strength and grinding ends is strongly recommended for HSC above at least 90 to 100 MPa (about 12.5 ksi to 14 ksi). Differences in careful end preparation are apparently minimal at lower strength levels.

Tests of in-place properties of HPC, particularly strength and permeability, have been reported. Haque et al. [1991], discussed the estimation of in situ strength of a variety of low, medium and high strength concretes compared to standard cylinders. They found that in situ strengths were 80% to 85% of cylinder strengths.

Air permeability tests, developed to provide a relatively quick measure of the permeability of concrete, particularly in-place, have increased in popularity. However, the sensitivity of the test to the moisture content of the concrete has limited its utilization due to concerns over interpretation of data. Concrete absorption tests, such as the Initial Surface Absorption Test, or ISAT, have also been used to characterize concrete permeability with some success. The low absorption of mature, low W/CM ratio concretes has reduced the use of this test on HPC. However, it appears well suited to lab studies, especially of deteriorated concrete.

One of the important applications of existing testing methodology was to the determination of early strength of HPC. Accurate determination of in-place strength is essential to insure that the pavement can be safely opened to traffic. Testing based on maturity concepts or using match cure systems to estimate the in-place strength of concrete was conducted in several early-to-open HPC pavements.

Both SHRP C-205 and SHRP C-206 successfully used conventional maturity methods to estimate the concrete strength in-place on several pavements constructed with HPC. SHRP C-206 used a match cure system which kept cylinders at the same temperature as the concrete in the pavement so that the compressive strength of the cylinder could be used to estimate the in-place strength. SHRP C-205 used a simpler, more cost effective system of keeping the test cylinders insulated until testing. This method was found to keep the cylinders at approximately the same temperature as the pavement so that the measured strength of the insulated cylinders provided a reasonable estimate of the in-place strength.

SHRP C-206 also investigated the use of pulse velocity in estimating the in-place strength of the pavements. Small access holes were left in the pavement to permit the use of conventional test apparatus. Another SHRP C-206 development was determination of the water content of concrete by microwave. However, this procedure proved highly variable.

Another w/c ratio gauge has been recently developed by Troxler, Inc., who have provided nuclear density gauges to the pavement construction industry for decades. This apparatus holds promise for accurately assessing both the water and cement content of mixes as batched. This product is still undergoing modifications and adjustments, but a substantial testing program was recently completed by the Highway Innovative Technology Evaluation Center (HITEC), which was established by the Federal Highway Administration and the American Association of State Highway and Transportation Officials. Preliminary evidence [HITEC 1996] suggests that the Troxler Model 4430 water-cement g in quality testing of concrete as delivered.

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