DESIGNING HPC FOR TODAY'S PRECAST/PRESTRESSED BRIDGE BEAMS

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ABSTRACT

High early strength is the concrete characteristic most desired in construction of precast/prestressed bridge beams, where productivity depends on timely release of prestressing force. The concrete strength required for release usually governs the mixture design. But achieving high early strength alone is insufficient; other concrete characteristics are essential as well. The challenge unique to the precast/prestressed concrete industry is achieving high early strength in harmony with adequate workability and high ultimate strength. While not necessarily incompatible or conflicting, these performance requirements are increasingly at odds as the limits of high performance concrete (HPC) are pushed.

Keywords: High performance concrete, Water/cementitious materials ratio (w/cm), Cement content, Supplementary cementitious materials, Type III cement, Chemical admixtures, Heat curing

INTRODUCTION

High early strength is the concrete characteristic most desired in construction of precast/prestressed bridge beams, where productivity depends on timely release of prestressing force. The concrete strength required for release usually governs the mixture design.[1] But achieving high early strength alone is insufficient; other concrete characteristics are essential as well. The challenge unique to the precast/prestressed concrete industry is achieving high early strength in harmony with adequate workability and high ultimate strength. In construction of bridge beams, the industry is now encountering the need to achieve 60 MPa (8,700 psi) inside of 1 day and 100 MPa (14,500 psi) by 28 or 56 days as span and spacing continue to expand. Adequate workability is required for efficient placement and consolidation into narrow, congested sections. While not necessarily incompatible or conflicting, these performance requirements are increasingly at odds as the limits of high performance concrete (HPC) are pushed. When designing HPC to satisfy multiple performance requirements, it is helpful to survey all the options and understand when these are beneficial and when these are detrimental.

EXPERIMENTAL PROGRAM

A study was performed to identify suitable materials and develop HPC mixtures for precast/prestressed bridge beams. Altogether, more than one hundred HPC mixtures were evaluated. Mixtures were designed on the basis of high early strength potential while providing adequate workability and long term strength development. Among the options for achieving high early strength, workability and high ultimate strength:

- Low water/cementitious materials ratio (w/cm)
- Increased cement content
- Supplementary cementitious materials
- ASTM C 150 Type III cement
- Chemical admixtures, including superplasticizers, air entraining (AE) admixtures, and corrosion inhibiting/strength accelerating (CI/SA) admixtures
- Heat curing

What follows is a discussion of these various options supported with experimental results.

EXPERIMENTAL PROCEDURES

Work was performed in the laboratory. Batching and testing procedures conformed to the applicable ASTM standards except mixing time, which was often extended beyond the duration specified in ASTM C 192 and continued until the concrete appeared uniform.[2,3] Batch weights were adjusted for aggregate moisture.

All mixtures contained crushed limestone as coarse aggregate and natural river sand as fine aggregate. The quantity of coarse aggregate was typically 1,000 kg/m^3 (1,686 lb/yd^3) and it met the No. 8 grading requirements of ASTM C 33 with a nominal maximum size of 10 mm

($^3/_8$ in). The quantity of fine aggregate was adjusted according to the absolute volume method. All mixtures also contained ASTM C 494 Type A water reducing admixture and Type A/F or Type F superplasticizer.

Concrete cylinders were cast in 100 x 200 mm (4 x 8 in) molds and consolidated by rodding. Cylinders were cured at 23 °C (73.4 °F) and 50% relative humidity during the initial 24 hrs. After 24 hrs and until tested, cylinders were moist cured (under water) at a temperature of 23 °C (73.4 °F) as specified by ASTM C 192.

Cylinders were tested for compressive strength at ages of 1, 28 and 56 days. Tests followed the procedures of ASTM C 39. Three to five cylinders were tested at each age. Many mixtures were batched multiple times to increase accuracy of the results. If batched more than once, the result was reported as an average of individual batch results.

EXPERIMENTAL RESULTS, ANALYSIS AND DISCUSSION

Designing HPC to satisfy multiple performance requirements is an exercise of choosing among several options. In Table 1, the options for achieving high early strength, workability and high ultimate strength are graded as beneficial or detrimental where appropriate. These grades reflect general guidelines and are based on the data of this research program and a synthesis of the literature.

Table 1. Options For Achieving High Strength & Workability

	Early Strength	Workability	Ultimate Strength
Low w/cm	△	▼	△
Increased Cement Content		△	
Supplementary Cementitious Materials		△	△
Type III Cement	△	▼	
Superplasticizing Admixture	△	△	△
AE Admixture	▼	△	▼
CI/SA Admixture	△		△
Heat Curing	△		▼

△ Beneficial ▼ Detrimental

LOW W/CM

The w/cm was identified as the most significant variable for producing HPC.[4] A low w/cm is beneficial to both early strength gain and ultimate strength potential. In Figure 1, simple linear regression models were created to describe the relationship between strength and w/cm. The regression lines represent the results from 125 HPC mixtures. These mixtures were designed with a variety of materials and proportions, with 94 of the mixtures containing Type III cement and w/cm's ranging from 0.406 to 0.220. The evidence suggests, at ages of 1, 28 and 56 days, that strength generally increases as the w/cm is lowered.

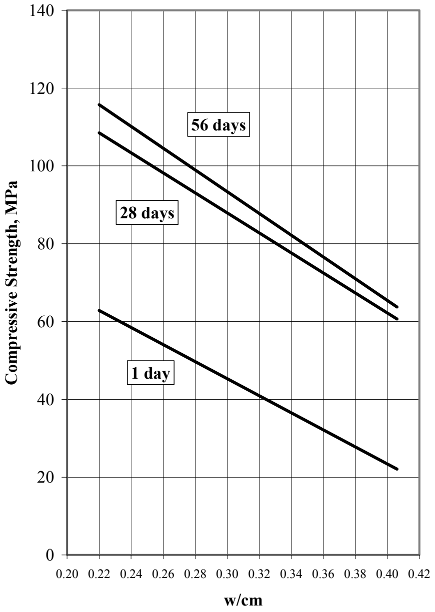


Figure 1. Compressive Strength and w/cm

There a point when decreasing the w/cm fails to increase strength. Having a low w/cm may result in an incomplete cement hydration due to lack of water required for the process.[5] The theoretical minimum w/cm for complete cement hydration varies widely from about 0.20 to 0.40. It depends on the specific combination of cementitious materials and the physical and chemical characteristics of those cementitious materials.[6,7] In HPC, ultimate strength potential may be limited by the amount of water available for hydration or by the intrinsic strength of the coarse aggregate.[6,8]

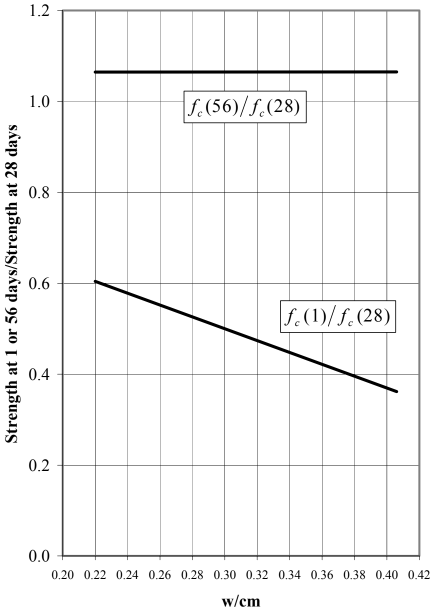


Figure 2. Rate of Strength Gain and w/cm

Results from the same 125 HPC mixtures also demonstrate that the rate of early strength gain increases with lower w/cm. In Figure 2, regression models describe strength gain at 1 day relative to strength at 28 days and also strength gain at 56 days relative to strength at 28 days. In Figure 2, f_c is defined as the average measured compressive strength. Strength gain at 1 day was found to be as much as 60% of corresponding strength at 28 days. The lower w/cm and the proximity of the cement particles increases the rate of cement hydration.[6] In contrast, between 28 and 56 days, the rate of strength gain was found to be independent of w/cm. Across the range of w/cm's, a nearly identical rate of strength gain was observed between 28 and 56 days.

Lowering the w/cm is detrimental to workability. When working in summer, HPC mixtures designed at low w/cm's may be especially difficult to place, consolidate and finish. Workability requirements put a practical limit on how low the w/cm can be designed.

INCREASED CEMENT CONTENT

Increases of cement content at a constant w/cm do not necessarily influence compressive strength, in conventional concrete or in HPC.[6,9] Guidelines for concrete mixture design by both the Portland Cement Association and ACI 363 identify relationships between compressive strength and w/cm, but not compressive strength and cement content. One study of conventional concrete found that increases of cement content at a constant w/cm actually decreases strength.[10]

A series of HPC mixtures with a w/cm of 0.30 and Type III cement were examined in this study to evaluate the effects of increasing cement content. Cement content of these mixtures ranged from 400 to 750 kg/m^3 (674 to 1,265 lb/yd^3). Slump and compressive strength results are illustrated in Figure 3. A strength plateau was reached at a cement content near 500 kg/m^3 (843 lb/yd^3). Beyond this point, increasing cement content did not significantly improve strength development, at 1 or 28 days. The modest increase in strength that was observed with increasing cement content might be attributed to an increase in the heat of hydration.

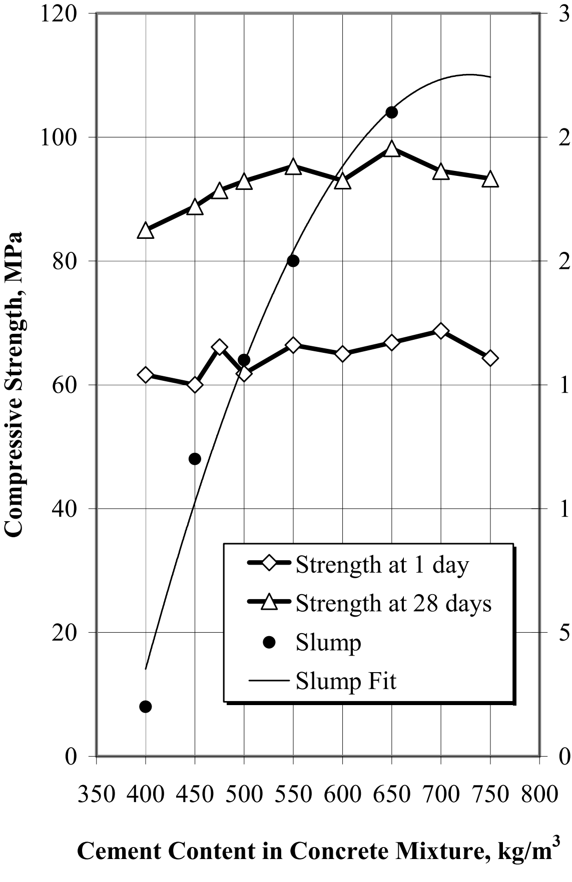


Figure 3. Changing Cement Content with a Constant w/cm

Increasing the cement content in an HPC mixture is often necessary for adequate workability. Slump measurements and a second order polynomial trendline are portrayed in Figure 3. Increasing cement content at the same w/cm was observed to enhance slump, which is an approximate measure of workability. Simply explained, more water is available for lubrication of the fresh concrete, especially after a superplasticizer is introduced. If slump of 150 mm (6 in) is desired for workability then, according to these results, a mixture with a minimum of 500 kg/m^3 (843 lb/yd^3) cement is necessary. Sometimes in practice, an increase in the cement content is accompanied by a decrease in the w/cm at the same workability. It is advisable to increase cement content sparingly to avoid escalating the cost of the mixture as well as amplifying heat during curing and the danger of cracking.

SUPPLEMENTARY CEMENTITIOUS MATERIALS

Supplementary cementitious materials such as fly ash are frequently employed in HPC mixtures. Partial replacement of cement with supplementary cementitious materials usually, but not always, improves workability. Supplementary cementitious materials enhance workability by moderating the temperature rise of fresh concrete. The spherical shape of fly ash particles also contributes to workability. Largely pozzolanic in composition, supplementary cementitious materials convert weak calcium hydroxide into strong calcium silicate hydrate, enhancing strength development.

Three similar mixtures were examined in this study to evaluate the effects of an ASTM C 618 Class C fly ash. These mixtures contained 550 kg/m^3 (930 lb/yd^3) cementitious material, including Type III cement, at a w/cm of 0.28. One mixture was designed without fly ash. A second mixture was designed with 10% fly ash replacement. A third mixture was designed with 20% fly ash replacement. Compressive strength results are illustrated in Figure 4. Fly ash replacement was detrimental to early strength gain. Fly ash replacement of 20% curbed strength at 1 day more than fly ash replacement of 10%. However, heat curing may be offsetting in this respect. In one study, HPC mixtures containing supplementary cementitious materials responded at 1 day to heat curing more positively than mixtures with Type III cement only.[11] Both mixtures containing fly ash achieved higher strength at 28 and 56 days than the mixture without fly ash. At 28 days, the mixture with 10% fly ash was best and at 56 days the mixture with 20% fly ash was best.

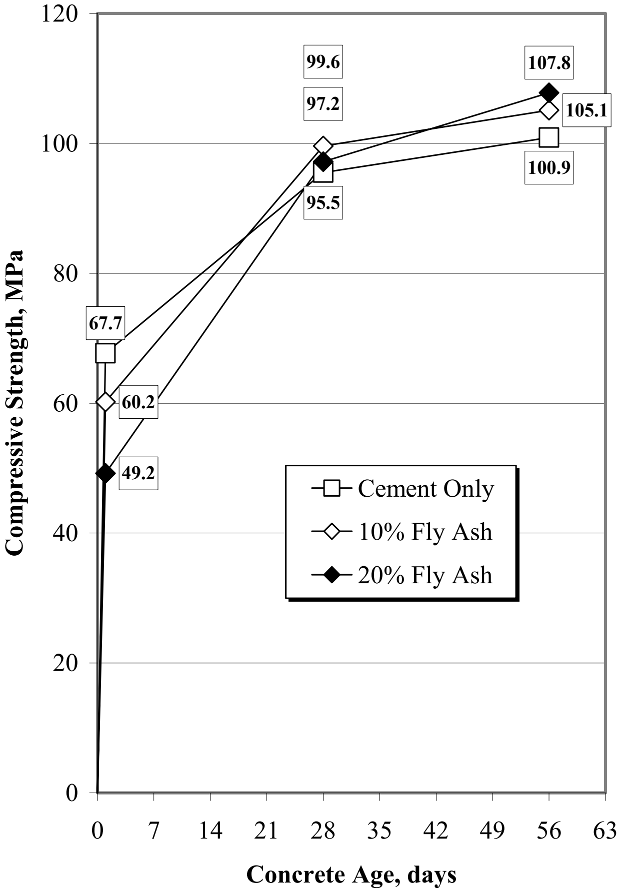
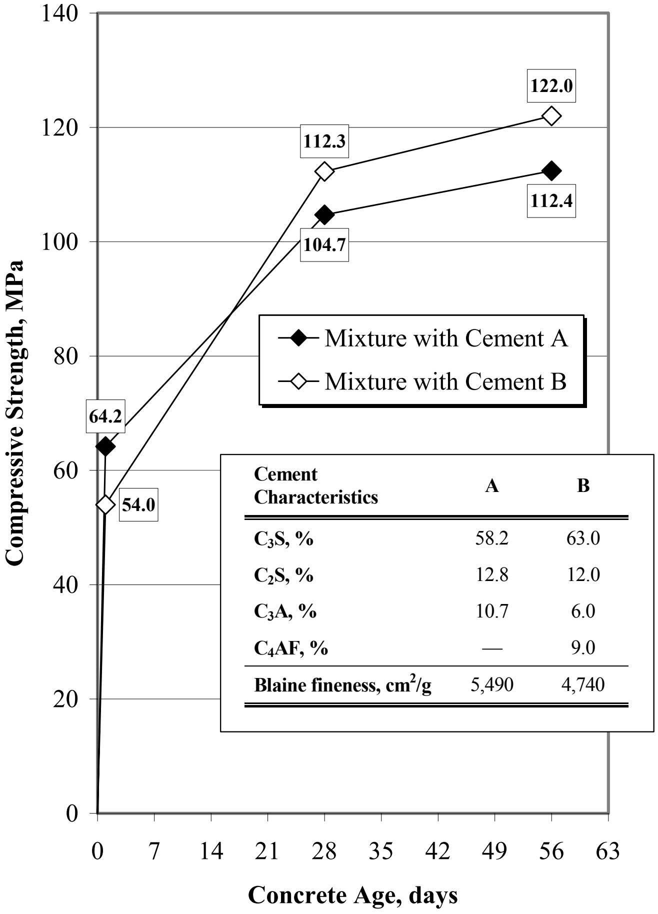


Figure 4. Fly Ash Replacement Rate and Compressive Strength Gain

TYPE III CEMENT

The precast/prestressed concrete industry typically uses Type III cement. The physical and chemical characteristics of Type III cement produce relatively rapid hydration activity and early strength gain. Still, among Type III cements, there can be substantial differences. Two Type III cements, identified as A and B, were compared in similar HPC mixtures. These mixtures contained 510 kg/m^3 (860 lb/yd^3) cement, and also 60 kg/m^3 (100 lb/yd^3) fly ash and 30 kg/m^3 (50 lb/yd^3) silica fume. The w/cm of these mixtures was 0.24. Cement characteristics and compressive strength results are presented in Figure 5. High tricalcium silicate (C_3S) and high fineness are beneficial to early strength gain. In this case, the mixture with cement A, which had higher fineness but lower C_3S than cement B, achieved higher strength at 1 day. The mixture with cement B achieved higher strength at 28 and 56 days.



Cement Characteristics	A	B
C_3S, %	58.2	63.0
C_2S, %	12.8	12.0
C_3A, %	10.7	6.0
C_4AF, %	—	9.0
Blaine fineness, cm^2/g	5,490	4,740

Figure 5. Comparing Two Type III Cements

HPC mixtures designed with Type III cement at low w/cm's can have harsh workability, especially when working in summer. Type I or Type II cements usually produce better workability than Type III cements, and are possibly better for ultimate strength development, especially if these have increased quantities of dicalcium silicate (C_2S).

CHEMICAL ADMIXTURES

Chemical admixtures are commonly employed in HPC mixtures. The most important of these in construction of precast/prestressed concrete bridge beams are superplasticizers, which are necessary for design of low w/cm's. As a rule, superplasticizers are necessary when the w/cm is below 0.40 to provide satisfactory workability.[6,12] Superplasticizers have a powerful dispersing effect on cement particles which facilitates an efficient hydration process and enhances strength development. The addition rate must be properly adjusted for different mixtures and conditions because superplasticizers can retard setting and early strength gain.

Superplasticizers have tremendous aptitude for increasing slump. Many trial mixtures without observable slump before addition of superplasticizer had slumps exceeding 230 mm (9 in) after addition and final mixing. Still, many superplasticizers have limitations. HPC mixtures can remain viscous or “sticky” and undergo rapid stiffening before adequate time for placement.

In situations where a concrete structural member will be exposed to cycles of freeze/thaw, an ASTM C 260 air entraining (AE) admixture is commonly specified in the interest of durability. Air entrainment is considered necessary for freeze/thaw resistance unless the w/cm is below 0.21 and compressive strength exceeds 138 MPa (20,000 psi).[13] AE admixtures are known to be detrimental to strength potential. It was observed in this study that strength was reduced about 6.6% for every 1.0% increase in air content. However, AE admixtures are beneficial to workability by creating countless tiny, discrete air bubbles in the fresh concrete. By improving workability, use of an AE admixture can allow a reduction in the w/cm.

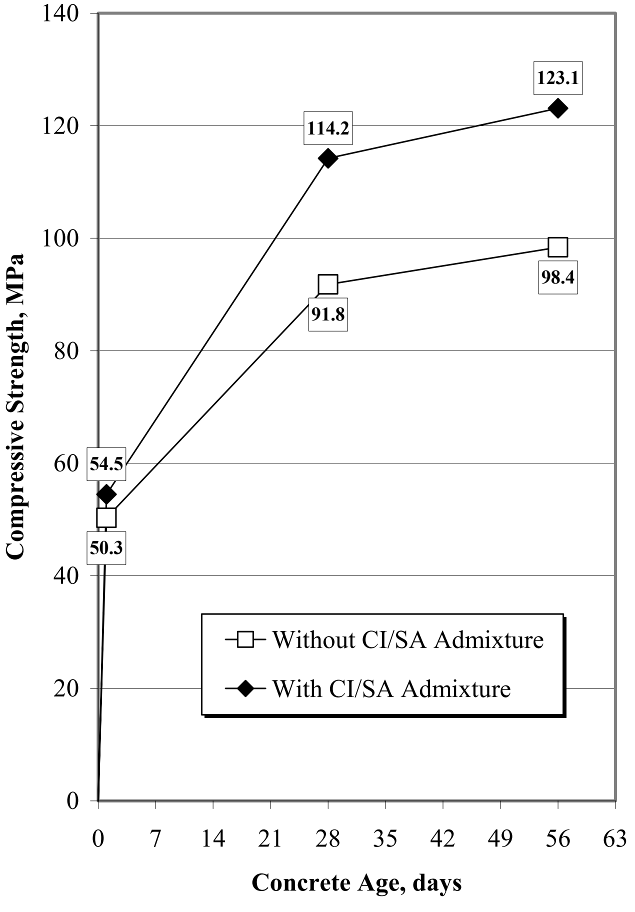


Figure 6. Strength Enhancement Observed with a CI/SA Admixture

An ASTM C 494 Type C corrosion inhibiting/strength accelerating (CI/SA) admixture containing calcium nitrite was found effective for enhancing strength gain, both at early ages and long term. Two HPC mixtures were examined to evaluate the effects of a CI/SA admixture. These mixtures contained 510 kg/m^3 (860 lb/yd^3) Type III cement, and also 60 kg/m^3 (100 lb/yd^3) fly ash and 30 kg/m^3 (50 lb/yd^3) silica fume. The w/cm of these mixtures was 0.26. Compressive strength results are illustrated in Figure 6. The mixture containing the CI/SA admixture achieved higher strength at all ages. At 1 day, the CI/SA admixture improved strength by 8%. By 28 and 56 days, the improvement with the CI/SA admixture was 24% and 25%, respectively. The CI/SA admixture was not detrimental to workability, at least when adhering to the suggested additions rates. But too excessive an addition rate can cause rapid set, dramatically reducing the time available for placement, consolidation and finishing.[14] Precast/prestressed concrete plants don't normally use accelerating admixtures during the summer.[15]

HEAT CURING

Heat curing has been employed by the precast/prestressed concrete industry in construction of bridge beams to increase productivity. Heat curing spurs rapid hydration activity and may enhance early strength gain. However, heat curing can also stunt ultimate strength development.

The effects of heat curing on HPC are largely unknown. Heat curing of HPC designed with Type III cement has been shown to increase early strength gain by more than 50% relative to ASTM standard curing.[16] Likewise, heat curing has been shown to increase the rate of strength gain. In 1 day, mixtures subjected to heat curing can gain as much as 90% of corresponding strength at 28 days, where 50% to 60% are typical values under standard curing.[17,18] But while it is generally agreed that heat curing enhances the early strength development of HPC with Type III cement, there is no consensus on how heat curing affects ultimate strength potential. According to different studies, ultimate strength potential, as measured at 28 or 56 days, may be negatively impacted by heat curing or, conversely, insensitive to the curing scheme, whether heat curing or standard curing. The negative impact of heat curing was found to be 25% on average.[16,19]

SUMMARY AND CONCLUSIONS

Achieving high early strength in harmony with adequate workability and high ultimate strength is a challenge facing the precast/prestressed concrete industry in construction of bridge beams. There are several options for elevating early strength gain. Among these options is design of a low w/cm and the use of Type III cement, certain chemical admixtures, and heat curing. Frequently, however, these options compromise workability or ultimate strength development.

Lowering the w/cm increases strength but is detrimental to workability. Also, lowering the w/cm increases the rate of early strength gain and, in 1 day, HPC mixtures can achieve up to 60% of 28 day strength under standard curing. Increasing cement content at a constant w/cm does not necessarily increase strength. Using a Type III cement at a w/cm of 0.30, a strength plateau was reached at a cement content near 500 kg/m^3 (843 lb/yd^3). However, increasing cement content at a constant w/cm enhances workability. Use of fly ash as a partial replacement of cement can enhance workability and ultimate strength development. HPC with fly ash and/or other supplementary cementitious materials has relatively slow early strength gain, but responds well to heat curing. Type III cement is typically employed in precast/prestressed concrete bridge beams where its high fineness enhances early strength gain. But in terms of workability and ultimate strength potential, Type I or Type II cements may be preferable. Superplasticizers are beneficial in all respects. An air entraining admixture, although beneficial to workability, substantially reduced strength. A corrosion inhibiting/strength accelerating admixture containing calcium nitrite was found beneficial to both early and ultimate strength and did not affect workability. Use of a CI/SA admixture increased strength more than 20% at 28 and 56 days. Finally, heat curing can enhance early strength gain in some HPC mixtures. But heat curing is almost always detrimental to ultimate strength development.

When designing an HPC mixture to satisfy multiple performance requirements, it is helpful to survey all the options and understand how these are sometimes both beneficial and detrimental. Trial batching is necessary to determine the best mixture for the specific application.

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