EFFECT OF SURFACE AREA TO VOLUME RATIO AND ACCELERATED CURING ON THE MECHANICAL PROPERTIES OF HIGH STRENGTH CONCRETE

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ABSTRACT

In order to investigate the effects of the SA/V ratio and accelerated curing on the mechanical properties of high-strength concrete (HSC), a series of experiments were executed in the materials and structural engineering laboratories at the University of Missouri-Rolla as well as a local Precast/Prestressed Plant. This experimental study was carried out using a commercially available match curing system involving four distinct phases developed to investigate the combined effect of accelerated curing and surface area to volume effects. The study examines various quality control / quality assurance aspects of high-strength precast prestressed girders.

Keywords: Surface Area-to-Volume; Accelerated Curing; Compressive Strength; High Strength Concrete; Quality Control / Quality Assurance of HSC; Match Curing.

INTRODUCTION

Utilizing high strength concrete (HSC) in structural members has greatly increased due to the growing demand for taller structures, longer spans and smaller member cross-sections. Researchers have demonstrated continuous interest in the effects of the mechanical properties of HSC, compared to the normal strength concrete (NSC). It has been reported (Cetin[4]; Balendran et al.[2]; Lura et al.[7]) that HSC may lead to a higher hydration temperature, which results in higher early-age strength, but lower later-age strength of the concrete. Numerous researchers have reported the significant differences between the strength of current standard quality control specimens and the in-situ strength in the member (Urpani et al.[11]; Myers and Carrasquillo[9]; Yang et al.[12]). In addition to the cementitious material content in the mix design, the curing condition of the concrete and the surface area-to-volume (SA/V) ratio of the structural member play an important role on the concrete hydration temperature[5], which affects the mechanical properties of the concrete.

According to Harrison[5], there are 5 factors that affect the hydration temperature. They are 1) types and quantities of cementitious materials; 2) size and shape of the section; 3) insulating effectiveness of the formwork; 4) concrete placing temperature and 5) ambient condition. The actual hydration temperature within the member is some combination of these five factors. Among these factors, size and shape of the section, which can be evaluated by SA/V ratio, has been little studied.

In the past, research studies on SA/V ratio of concrete members were limited to studies on mass concrete, where thermal behavior and cracking were generally regarded as the primary concern rather than the compressive strength[1]. Mass concrete practices are developed largely for concrete dam construction, where temperature-related cracking is first identified and high compressive strength is usually not required. As HSC has been widely applied in recent years to structural members, especially in the Precast / Prestressed industry, the effects of mass concrete on strength has been noted. Though these members have relatively higher SA/V ratio than mass concrete such as gravity dams, they often have higher hydration temperature rise due to the combined affects of high cementitious contents and low SA/V ratio. Such temperature rise will greatly affect the early-age and later-age strength of the member. To date, few research studies have been carried out to characterize the relationship between the SA/V ratio and the compressive strength of HSC.

Most often precast plants fabricate typical AASHTO-PCI standard sections. Other standards include state DOT standard sections such as Missouri and Washington. The SA/V ratios of these standard girder sections and the corresponding end block ratios range from 0.09 1/in. (3.5 1/m) to 0.45 1/in. (17.7 1/m). While the SA/V ratio for standard quality control/quality assurance (QC/QA) specimens including 4 x 8-in. (100 x 200 mm) and 6 x 12-in. (150 x 300 mm) cylinders are 1.0 1/in. (39.4 1/m) and 0.67 1/in. (26.3 1/m) respectively. As illustrated in Figure 1, the distribution of SA/V ratios of different types of sections and the standard QC/QA specimens is quite broad. These large variations in SA/V ratios may not result in large differences in mechanical properties for low content of cement mixes (or high *w/cm* mixes). However, the effects of SA/V ratio on the structural member and quality control specimens cannot be ignored when HSC is selected. Many research studies on the quality control testing of HSC relating to the precast / prestressed plant have been conducted in recent years. It has been reported (Carlton[3]; Kehl[6]; Myers[8]) that HSC precast beams experience significant heat development during curing, which can result in large temperature gradients and reduced strength at later-ages. Kehl[6] concluded that current procedures for curing quality control specimens in the precast concrete industry produce specimens which are subjected to curing temperatures that can be very different than the actual concrete in the member. He further recommended that match curing technology should be used for curing quality control specimens in the precast concrete industry without regard to SA/V ratio or cement content.

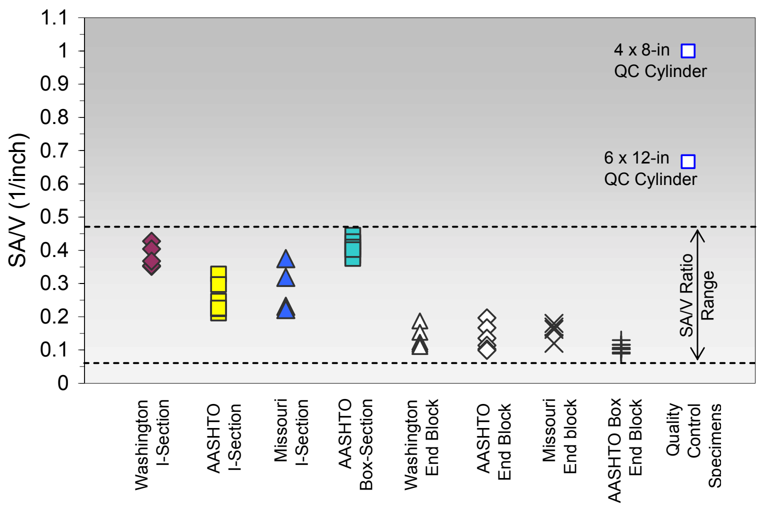


Figure 1. Distribution of SA/V Ratios of Standard Sections

Match curing technology, which is also referred as temperature-matched curing, cures the specimens under the same temperature development profile within the member. The actual temperature profile that the match curing system follows can be from the concrete member measured by thermocouple wires in real time, or from pre-programmed data using the controller. The system controls the heater / cooler to allow the match-curing specimens maintain the same temperature as desired. Recently match curing technology has been used in both laboratory and in-situ field environments where the actual strength of the concrete needs to be evaluated to a higher level of precision. The primary use in the field to date has been to determine when release strength requirements are met for prestressed / precast members.

Match curing technology provides a method for evaluating the actual concrete strength at any location in a structural member, as well as simulating any hydration temperature development profile for research studies. It can remove the unreliable estimation that is based on experiences from concrete casting operations and provide a more accurate prediction of time for formwork stripping, prestressing or lifting operations.

RESEARCH SIGNIFICANCE

Current quality control specimens have been found to underestimate the early-age strength but overestimating the later-age strength of high strength concrete (HSC) girders in precast /

prestressed industry.[8] This paper presents a better understanding of the effects of surface area-to-volume and accelerated curing on the mechanical properties of HSC and the adequacy of current quality control specimens in the precast industry. Results from this study address the applicability of match curing technology as a primary quality control tool in the precast industry.

EXPERIMENTAL PROGRAM

MATERIALS

The concrete mixtures in this experiment were prepared with commercially available cement that met the specifications of ASTM C1157 for Type GU and ASTM C150 for Type I cement. Locally available crushed limestone aggregate with a nominal particle size of 14 mm (9/16 in.) and a well-graded natural river and with a fineness modulus of 2.5 were used. The SSD of the coarse aggregate and fine aggregate were 2.73 and 2.5, respectively, and their absorption levels were 1.41% and 1.40%, respectively. Lignite and sub-bituminous coal fly ash (ASTM Class C Fly Ash) was used as a cementitious replacement material. A commercially available high-range water reducer (HRWR) that satisfied ASTM 494 requirements was used to increase the slump and workability of HSC in this study.

MIX PROPORTIONS

As summarized in Table 1, the investigated mixtures were prepared with a *w/cm* of 0.25 and 0.30 within the range of HSC for most applications in precast / prestressed industry.

Table 1. Mixture Proportions of Investigated Concrete

	w/cm=0.25		w/cm=0.30
Mix Designation	L25	L25FA	L30
Materials	100% cement	65% cement + 35% fly ash	100% cement
Cement, lb/yd^3 (kg/m^3)	988 (586)	642 (381)	642 (381)
Fly ash, lb/yd^3 (kg/m^3)	0 (0)	346 (205)	0 (0)
Coarse aggregate, lb/yd^3 (kg/m^3)	1918 (1138)	1918 (1138)	1965 (1166)
Fine aggregate, lb/yd^3 (kg/m^3)	1029 (611)	1029 (611)	928 (551)
Mix water, lb/yd^3 (kg/m^3)	247 (147)	247 (147)	255 (151)
HRWR oz/yd^3 (ml/m^3)	200 (7,736)	200 (7,736)	127 (4,912)
Target Slump[1], inch (mm)	10 (254)	10 (255)	10 (256)

[1] Actual slump ranged from 9-11 in. (229-279 mm) at time of placement.

Thirty-five percent Class C fly ash replacement by weight (the maximum limit specified by ACI 211) was selected for one series of investigation (L25FA). The dosage of HRWR was adjusted during batching to obtain a final slump in the 9 to 11 in. (229 to 279 mm) range at placement.

SA/V CUBE SELECTION

Selecting the dimension and size of the cubes was based on SA/V ratios of standard member section and size constraints in the lab. After careful review of SA/V ratios of current standard sections available, seven cube molds were selected in the first phase to produce seven concrete cubes with SA/V ratios ranging from 0.30 ~ 1.0 1/in. (11.8 ~ 39.4 1/m) as tabulated in Table 2. Four values of 0.1, 0.2, 0.4, 0.6 1/in. (3.9, 7.9, 15.7, 23.6 1/m) were selected as the standard key SA/V ratios for match curing in phase III, which are similar to most standard cross-sections and end blocks in the field as well as quality control cylinders. The analysis and discussion of the research are based on the test results of these SA/V match-cured cylinders.

Table 2. Summary of SA/V Cube Dimensions

No.	SA/V (1/in.)	Dimension (LxWxH in.)	Volume (ft^3)	Description
1	1.00	6 x 6 x 6	0.125	Represents 4x8-in. cylinder
2	0.67	9 x 9 x 9	0.422	Represents 6x12-in. cylinder
3	0.50	12 x 12 x 12	1.000	Represent Standard Cross-Sections
4	0.45	13.5 x 13.5 x 13	1.371	
5	0.40	15 x 15 x 15	1.953	
6	0.35	17 x 17 x 17.5	2.927	
7	0.30	20 x 20 x 20	4.630	

Conversion: 1 inch = 25.4 mm

CURING TEMPERATURES

The principal of selecting the accelerated curing temperature was based on practice and current Department of Transportation (DOT) restrictions. The final design of curing temperatures for this research were room temperature, 130°F (54.4°C) and 160°F (71.1°C). Room temperature varied from 60 to 75°F (15.6 to 23.9°C) and was adjusted to 70°F (21.1°C) in Phase III. In order to reflect the behavior of HSC and simulate the actual practice in the field, accelerated curing temperature profiles for 130°F (54.4°C) and 160°F (71.1°C) were developed as shown in Figure 2. These two profiles were pre-programmed before curing the specimens in an environmental chamber that can automatically control the temperature.

QUALITY CONTROL SPECIMENS

ASTM Moist-cured Cylinder, Member-cured Cylinder and Match-cured Cylinder were considered and studied in this research. All of the specimens were 4 x 8-in. (100 x 200 mm) cylinders and were made according to the procedures of ASTM C192-00 (2000). For ASTM Moist-cured and Member-cured Cylinders, plastic molds were used. For match-cured cylinders, steel molds were used (see Figure 3). Member cured specimens were cured with the SA/V cubes, similar to member cured specimens in the precast industry that are cured along the bed line of prestressed / precast member. These specimens are often used by a precaster to verify release strength prior to release of the pre-tensioning strands.

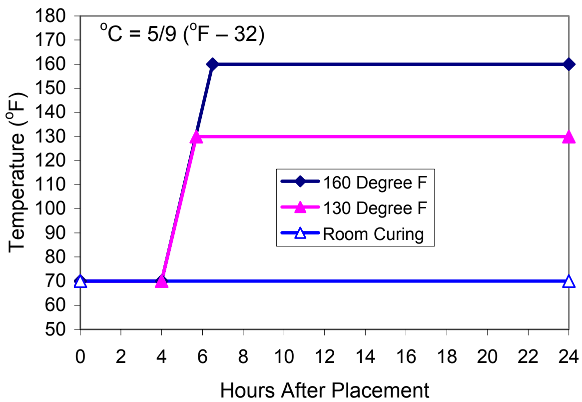


Figure 2. Accelerated Curing Temperature Profiles

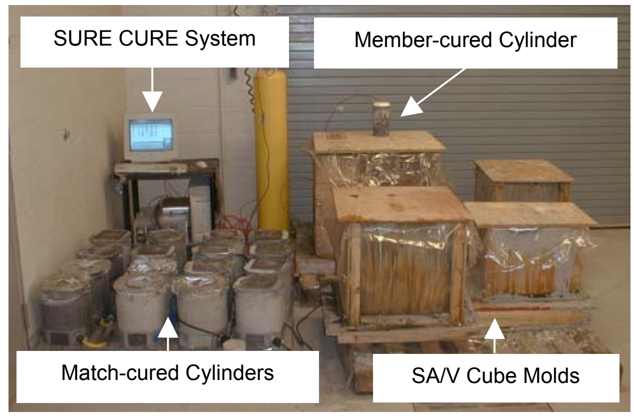


Figure 3. Test Setup in the Room Condition

TEST PROCEDURES

The program was sub-divided into two studies with a total of three phases. Phase I: Data Collection, measured the temperature development profiles of seven high strength concrete cubes that represent seven different SA/V ratios ranging from 0.30 to 1.0 1/in. (11.8 to 39.4 1/m) as shown in Table 3. Lower SA/V ratios were not feasible due to the limitations in lab facilities and batching capabilities.

Table 3. Summary of SA/V Cubes and Cylinders Measured in Phase I

No	Mix Proportion Designation	Curing Temperature	Cylinder	SA/V Ratio of the Cubes						
			4"x8"	1	0.67	0.5	0.45	0.4	0.35	0.3
1	L25	Room	√	√	√	√	√	√	√	√
2		130°F	√	√	√				√	√
3		160°F	√	√	√	√	√	√	√	√
4	L25FA	Room	√	√	√	√	√	√	√	
5		130°F	√	√	√		√			
6		160°F	√	√	√	√	√			
7	L30	Room	√	√	√		√	√		
8		130°F	√	√	√	√				
9		160°F	√	√	√	√				

Conversion: °C = 5/9 (°F – 32); 1 inch = 25.4 mm

These cubes were subjected to three ambient temperatures of room temperature, 130°F, and 160°F (54.4°C, and 71.1°C), two water to cement ratios (*w/cm*=0.25, *w/cm*=0.30) and two fly ash replacement levels (with / without 35% replacement of cement with fly ash by weight). Phase II: Profile Modeling, established the equations for the relationship between peak hydration temperature and SA/V ratio and modeled the temperature development profiles of each condition from the data obtained in phase I. Four values of SA/V ratio: 0.1, 0.2, 0.4, 0.6 1/in. (3.9, 7.9, 15.7, 23.6 1/m), were selected as the standard key points for match curing in the next phase. Phase III: Match Curing, match-cured 45 groups of 4 x 8-in. (100 x 200 mm) cylinders following the programmed temperature profiles developed in Phase II, as shown in Table 4. Release (24 hours) and 56-day compressive strength and modulus of elasticity of cylinders were measured respectively during this phase.

Table 4. Summary of the Standard Match Curing Cylinders in Phase III

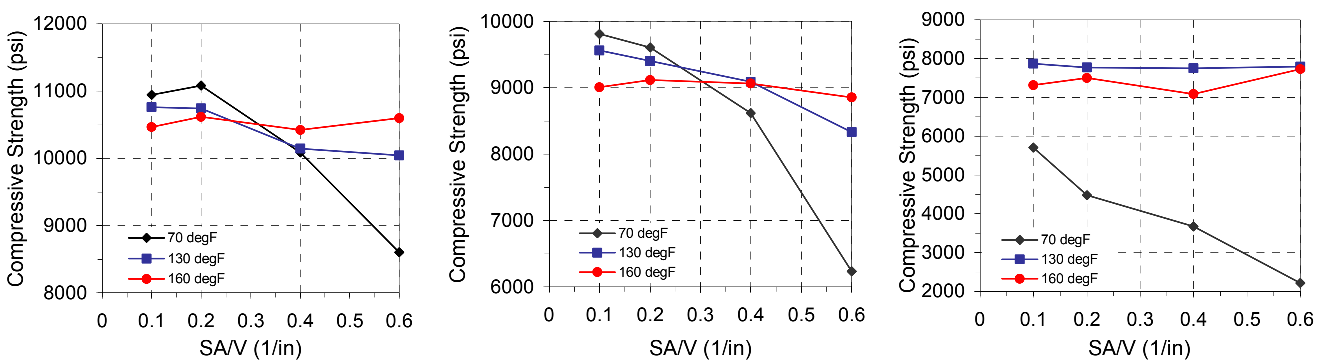
Group	Item	Description			Represents of SA/V Ratio of Cubes				
		w/cm Ratio	35% Fly Ash	Curing Temperature	0.1	0.2	0.4	0.6	1*
1	L25-70	0.25	NO	70°F	√	√	√	√	√
2	L25-130			130°F	√	√	√	√	√
3	L25-160			160°F	√	√	√	√	√
4	L25FA-70	0.25	YES	70°F	√	√	√	√	√
5	L25FA-130			130°F	√	√	√	√	√
6	L25FA-160			160°F	√	√	√	√	√
7	L30-70	0.3	NO	70°F	√	√	√	√	√
8	L30-130			130°F	√	√	√	√	√
9	L30-160			160°F	√	√	√	√	√
Notes : “*” represents of the member cured cylinder of 4 x 8-in. (100 x 200 mm) in corresponding group and served as the control cylinder.									

Conversion: °C = 5/9 (°F – 32)

TEST RESULTS – MECHANICAL PROPERTIES

The compression strength and modulus of elasticity (MOE) were the two primary mechanical properties monitored at early-age (1 day) and later-age (56 days) for the specimens subjected to various SA/V ratios and accelerated curing. The term early-age corresponds to the time requirement for typical release age strength requirements, while the later-age corresponds to the typical design strength time requirement for HSC precast / prestressed concrete members. In this discussion only the compressive strength testing is presented due to publication space limitations. Figure 4 illustrates the compressive strength development at early-age versus the SA/V ratio and two accelerated curing levels 130°F (54.4°C) and 160°F (71.1°C) respectively. 70°F (21.1°C) was selected as the “lab curing” or ambient conditions to serve as a benchmark representing no accelerated curing. A temperature of 160°F (71.1°C) was selected as the maximum accelerated curing limit since this has been specified by several DOT's and was also a recommended limit by the author[8] previously. A temperature of 130°F (54.4°C) was selected as a moderate level of accelerated curing.

Figures 4a and 4b represent mix designs without mineral admixtures at w/cm ratios of 0.25 and 0.30 respectively, while Figure 4c represents a mix design with 35% fly ash replacement at 0.25 w/cm ratio. As the mass of the section increases (SA/V decreases) the compressive strength increases without accelerated curing. As accelerated curing is implemented, the rate of strength gain is dramatically affected. For the mix designs without mineral admixtures (see Figures 4a and 4b), as the accelerated curing temperature is increased the effectiveness to improve the compressive strength and thereby meet release strength requirements at an earlier time line is diminished. Therefore, for SA/V ratios in the range from 0.2 to 0.45 that are typical of traditional standardized sections, it may be noted that accelerated curing of HSC without mineral admixtures is relatively ineffective.

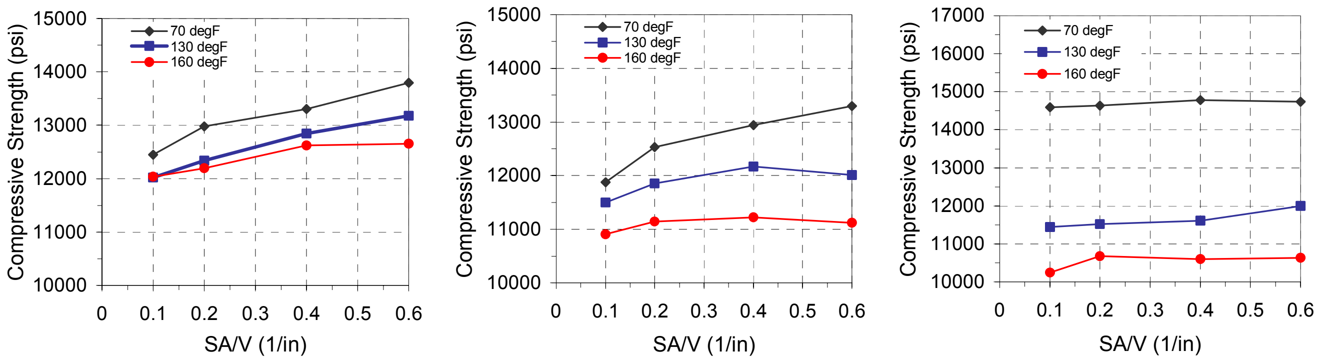


a) Mix L25 b) Mix L30 c) Mix L25FA

Figure 4: Compressive Strength Development at Early-Age (1 day)

Increasing the accelerated temperature from 130 to 160°F (54.4 to 71.1°C) for the mix design with fly ash replacement did not have a significant impact on compressive strength, but using accelerated curing or casting sections with a greater mass will generally result in higher compressive strength than companion sections without accelerated curing. Since the vast majority of HSC mixture proportions will incorporate mineral admixtures such as the Class C fly ash used in this case to reduce the unit cost of the concrete and help control temperature development, accelerated curing will provide some benefits, but perhaps not as much as realized with conventional mix designs with much lower target strengths.

Figure 5 illustrates the compressive strength properties at later-age (56 days). Controlling the temperature development at early-age is critical in developing greater later-age compressive strength as reported previously by many experts.



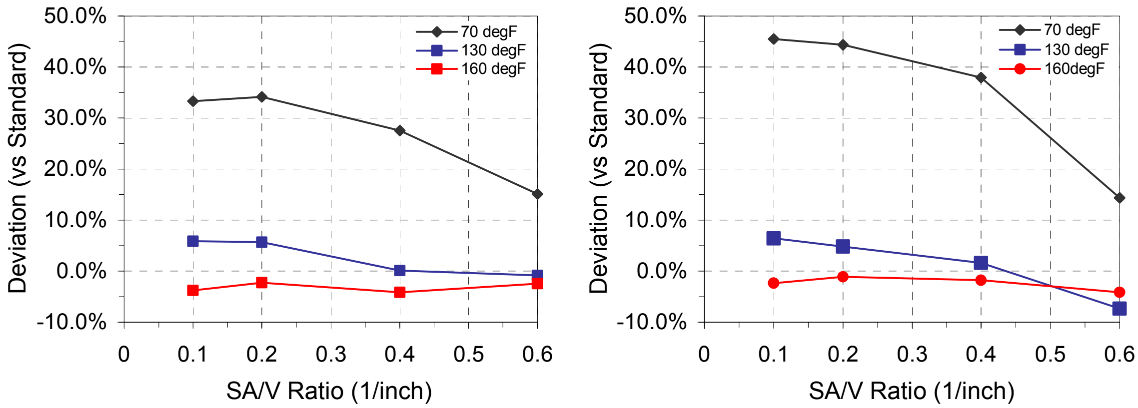
a) Mix L25 b) Mix L30 c) Mix L25FA

Figure 5: Compressive Strength Development at Late-Age (56 days)

Of particular interest in this study, is the rate of influence given the various SA/V ratios, temperature rise of the mix design, and accelerated curing temperature. Several conclusions can be drawn at later-age. While mix L25FA with the Class C fly ash replacement resulted in significantly lower strength levels at release, it resulted in the highest strength levels regardless of the SA/V ratio of the section without accelerated curing. The Class C fly appears to be much more temperature sensitive as the variation observed between the various accelerated curing levels is far greater than the counterpart mix designs. Accelerated curing the mix design with Class C fly ash replacement does help the early-age strength, but is severely detrimental to the late-age strength. The SA/V ratio for the mix with the Class C fly ash replacement did not appear to play a major role in the later-age compressive strength development; however, it was far more significant to the later-age compressive strength development of the mix designs without mineral admixtures.

DATA ANALYSIS – MATCH CURING IMPLEMENTATION

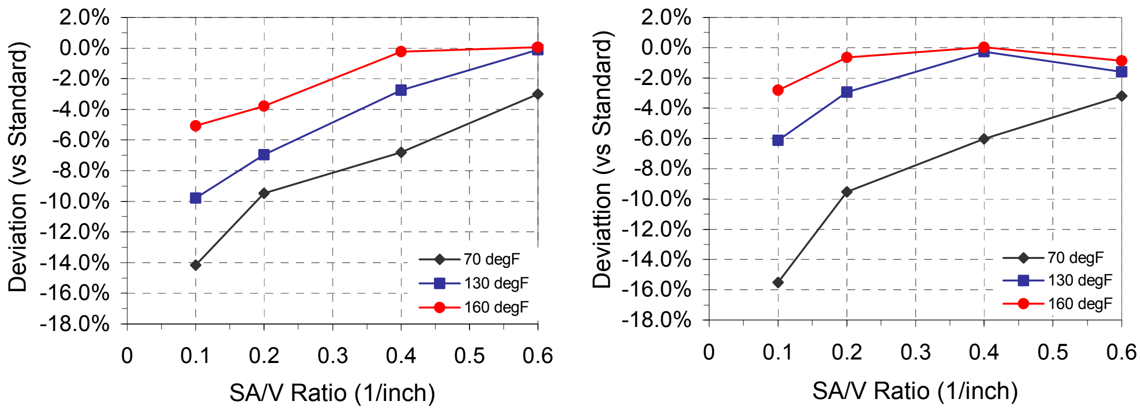
Data analysis was performed on the data obtained from mechanical property testing to examine the variation from the standard quality control specimens at early-age and late-age. It was desirable to examine the variation to see if a preliminary guideline could be developed to assist the precaster in the implementation of match curing technology based on the SA/V ratio and the cement content in the mix design. For this reason, two of the mix designs did not use any mineral admixtures so the study would examine mix designs that tended to develop higher temperature rise. As presented earlier w/cm ratios of 0.25 and 0.30 were selected since these tended to be representative w/cm ratio used at most precast plants for HSC sections. Figure 6 illustrates the variation in compressive strength between the member-cured specimen (labeled "standard") and the match-cured specimens for the variables investigated in this study. Variations at early-age of nearly 50% were observed between the match-cured specimens and the member-cured specimens for the specimens without accelerated curing emphasizing the high level at which current QC/QA methods underestimate compressive strength under certain situations.



a) Mix L25 b) Mix L30

Figure 6: Deviation of Match-cured Specimens from ASTM Member-cured at Early-Age (1 day)

Figure 7 illustrates the variation in compressive strength between the member-cured specimen (labeled "standard") and the match-cured specimens for the variables investigated in this study. Current QC/QA specimens overestimated compressive strength by nearly 16% without accelerated curing.



a) Mix L25 b) Mix L30

Figure 7: Deviation of Match-cured Specimens from ASTM Member-cured at Later-Age (56 days)

MATCH CURING AT LATER AGES

Using an acceptable variation of 5% between the current quality control specimen used at the precast plant (member-cured specimen) and the match-cured specimen, a guideline was developed by the authors. In essence, if the variation was 5% or less between the match-cured specimen and the member-cured specimen, it was felt by the authors that the member-cured specimen did an adequate job at strength prediction. For the HSC member without mineral admixtures where later-age (design age) compressive strength is a primary concern, Figure 8 illustrates a suggested guideline for selecting the critical SA/V ratio for using mach curing technology. It was developed using Figures 7a and 7b by adding second order curves. If the combination of water to cement ratio (w/c) and SA/V ratio is in the non-shaded region of Figure

8, the member-cured cylinder should not be used as the primary quality control cylinder. In these regions, the use of match curing technology is recommended to be used as the primary quality control method. As an example, if an AASHTO/PCI Type IV I-Beam girder is designed (SA/V=0.21 1/in., see Figure 1) to use HSC with the w/c = 0.27 and cured in an ambient environment around 70°F (21.1°C); as illustrated in Figure 8, match-curing technology is strongly recommended to accurately predict the release and design strength and other mechanical properties in the member.

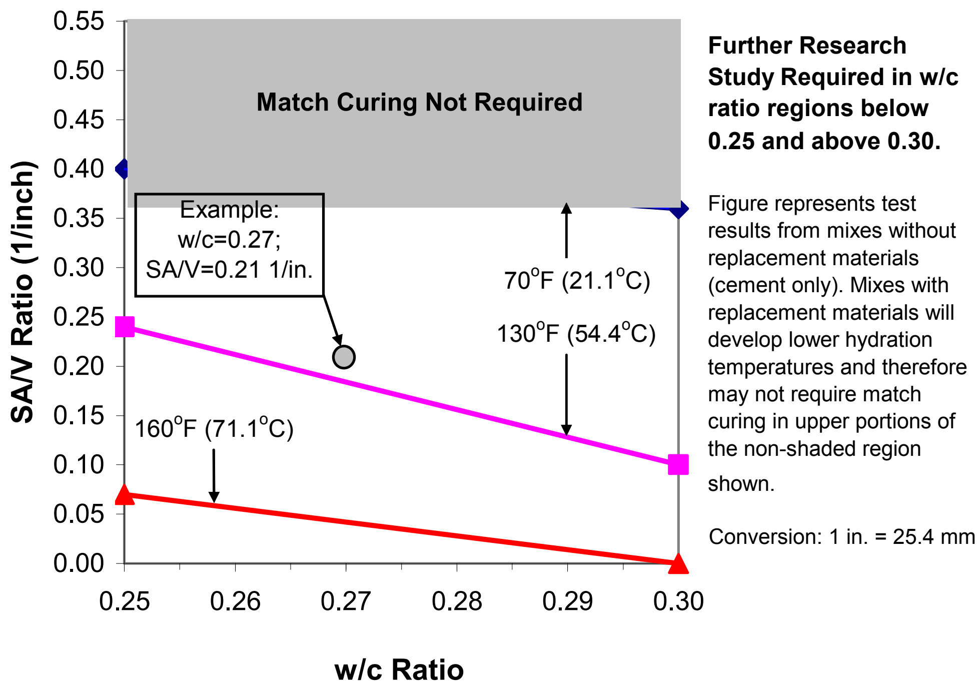


Figure 8. Guideline for Selecting Critical SA/V Ratio for Using Match Curing Technology for Design Compressive Strength

Figure 8 provides a quick and simple way to evaluate if the SA/V ratio affects the accuracy of the conventional quality control cylinder (member-cured cylinder) and whether a match curing system is recommended in practice. However, Figure 8 is derived from the experiments in the laboratory and field related to this research study. It has not been validated by other mix designs of HSC with different cement types and chemistry (in particular the fineness) or other mineral admixtures at a given w/cm ratio. However, it is expected that the results should be more on the conservative side as the governing case appears to be mix designs with cement only. This guideline should provide a starting point for a precaster or designer to better select his or her quality control method at the precast plant. It should be noted that for the mix design with fly ash replacement (Mix L25FA), the variation between member-cured and match-cured specimen did not exceed the 5% variation criteria adopted.

CONCLUSIONS

The following conclusions were drawn based upon the findings of the research study conducted herein.

Effect of SA/V ratio:

1) SA/V ratio has a significant impact on the compressive strength of HSC at early-age when it is cured under ambient condition around 70^{o}F (21.1^{o}C). The lower the SA/V ratio, the higher the compressive strength at early-age. However, for high cement content mixtures (w/c<0.25) compressive strength appears to degrade at early-age when the SA/V ratio is lower than 0.2 1/in. (7.9 1/m).
2) SA/V ratio has less impact on the compressive strength of HSC at early-age when a high accelerated curing temperature is applied.
3) SA/V ratio has a significant impact on compressive strength of HSC without replacement materials at later-ages.
4) SA/V ratio has almost no impact on the compressive strength of HSC with 35% fly ash replacement at early-age cured under high accelerated curing [above 130^{o}F (54.4^{o}C)].
5) In general, SA/V ratio has a limited impact on the compressive strength of HSC with 35% fly ash replacement under the curing conditions and mix constituents in this study.

Effect of accelerated curing temperature:

1) High accelerated curing temperature is only effective on attaining high compressive strength at early-age for high SA/V ratio [SA/V > 0.4 1/in. (15.7 1/m) of HSC without replacement materials. Accelerated curing does not increase the compressive strength at early-age for low SA/V ratio which is a key finding from a QC perspective with broad implications in the precast industry.
2) Increasing accelerated curing temperature to a threshold of a temperature between 70^{o}F (21.1^{o}C) and 130^{o}F (54.4^{o}C) can effectively increase the compressive strength of HSC with 35% fly ash replacement at early-age.
3) Without exception, accelerated curing temperature decreases the compressive strength of HSC at later-ages.
4) Use of accelerated curing with the intention to achieve high early-age strength is not applicable for massive HSC members without replacement materials. For SA/V < 0.4 1/in. it results in decreased later-age compressive strength with no increase in early-age strength.

Match curing technology is required if either of the following requirements is encountered:

1) Early-age compressive strength is a primary concern and no steam curing is applied [the curing temperature is approximately 70^{o}F (21.1^{o}C)] for all the current standard section beams investigated in this study including all types of AASHTO Box Beam, AASHTO I-Beam, Missouri I Girder and Washington I-Beam, as well as their end blocks.
2) Any point within the structural member that is required to be accurately evaluated for its mechanical properties at either early or later-age.

Use of Match Curing Technology:

1) Match curing technology is recommended if early-age compressive strength of HSC without steam curing is required and a concrete member with SA/V ratio less than 0.6 1/in. (23.6 1/m) is used.
2) Based on the mix designs studied herein, it is clear that match curing technology is not necessary for a HSC member of HSC with 35% fly ash replacement, for the criteria suggested within this research study.
3) For a HSC member without mineral admixtures where the later-age (design age) compressive strength is a primary concern, Figure 8 illustrates a suggested guideline for selecting the critical SA/V ratio for using the mach curing technology based on the study undertaken herein. If the combination of water to cement ratio (w/c) and SA/V ratio is in the un-shaded region, the member-cured cylinder should not be used as the primary quality control cylinder. In these regions, the use of match curing technology is recommended to be used as the primary quality control method.

Several recommendations to the precast/prestressed industry related to HSC structural members:
1) Accelerated curing or steam curing cannot be used effectively to increase the early-age strength of HSC members with low SA/V ratio [less than 0.2 1/in. (7.9 1/m) in this study] for mixes without replacement materials in the 0.25 – 0.30 w/c range.
2) Use of fly ash in HSC can greatly reduce the effect of SA/V ratio on later-age strength, but may also hamper attaining release strength requirements if used in large replacement levels. The compressive strength of HSC with fly ash replacement subjected to high accelerated curing temperature may dramatically affect later-age strength gain.
3) Member-cured cylinder can represent the actual later-age strength and early-age strength subjected to high accelerated curing temperatures [above 130^{o}F (54.4^{o}C)] for HSC with high replacement of fly ash.

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