# NEW TECHNOLOGY-BASED APPROACH TO ADVANCE HIGHER VOLUME FLY ASH CONCRETE WITH ACCEPTABLE PERFORMANCE

## *GUIDE FOR THE CONSTRUCTION TEAM*

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# New Technology-Based Approach to Advance Higher Volume Fly Ash Concrete With Acceptable Performance

## GUIDE FOR THE CONSTRUCTION TEAM

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# Disclaimer

## INTRODUCTION

This guide is an extension of the project "New Technology-Based Approach to Advance Higher Volume Fly Ash Concrete with Acceptable Performance" that was completed in August 2008. The project was sponsored by the Department of Energy through the Combustion Byproducts Consortium and the RMC Research & Education Foundation. The project addressed one of the major barriers to the large scale use of high-volume fly-ash (HVFA) concrete, namely the lower rate of early-age strength development compared with ordinary portland-cement concrete. The final report of that project has been published (Obla et al. 2008) and its primary conclusions are:

- For HVFA concrete, the large volume of structural elements will result in higher in-place temperatures and in increased early-age in-place strengths (measured by match-cured cylinders and pullout tests) compared with strength gain by cylinders under standard laboratory conditions. As a result, construction schedules may not have to be extended.
- Field-cured cylinders underestimated in-place strength development, and standard-cured cylinders must not be used for estimating in-place early-age strengths. Field cured and standard cured conditions are discussed in ASTM C31/C31M.
- The maturity method and the pullout test are applicable to estimate the early-age concrete strength in structures made with HVFA concretes. The use of these methods will allow for increased fly ash content without adverse effects on the safety of early-age construction operations.

This guide is for the construction team (contractor, concrete producer, and engineer) and provides recommendations on the application of the maturity method to support the use of optimized HVFA concrete mixtures by providing a simple method to estimate in-place strength development. The optimized HVFA mixture proportions will allow one to evaluate the lowest total cementitious materials contents and highest water-cementitious materials ratio (*w/cm)* that can be permitted for durability concerns that can still attain the early-age strengths required for that application.

This document does not seek to address all the durability concerns related to use of HVFA concrete. The user needs to ensure that all the performance requirements of the project are met.

## APPROACH

At the outset, it should be noted that the successful use of HVFA concrete on a project requires a team effort. As such, this guide is written for the whole team and each team member must play their role and latitude should be provided to permit the contractor and producer to develop an optimized HVFA concrete that meets the project requirements. The recommendations in this guide should not be used to develop prescriptive specifications because concrete suppliers and contractors who know their materials well can optimize the mixtures to satisfy the engineer's performance criteria. Design professionals that support sustainable development principles can use the concepts in this guide to minimize the "$CO_2$ footprint" of the concrete portion of a construction project (Concrete $CO_2$ Fact Sheet 2008). Because at this stage, such $CO_2$ calculators are not readily available, the design professional may be interested in using 50% fly-ash concrete for the project. The important caveat to this guide is that it should not encourage the specification of 50% fly ash for all concrete in the project. It should be kept in mind that for certain applications and exposure conditions HVFA concrete may not satisfy the performance criteria (Obla et al. 2005).

Concrete slabs that require a trowel finish is one type of application that may not support the use of HVFA concrete. Trowel finishing of concrete slabs requires a relatively short setting time because prolonged setting times can delay finishing and increase the propensity for plastic shrinkage cracking. Trowel finishing concrete slabs with a low *w/cm* of about 0.40 may be challenging due to the sticky nature of the concrete. Also, the reduced rate of bleeding will cause the surface to dry out early and encourage finishers to conduct the finishing operations too early and make the slabs more susceptible to delaminations. Therefore, for construction of trowel-finished slabs, it may be advisable to limit fly ash levels to about 30% to 40% (setting times can be shortened through the use of accelerating admixtures but this may increase concrete costs substantially particularly if non-chloride accelerating admixtures are used).

On the other hand, formed vertical structural members such as columns and walls are less impacted by factors such as finishability, plastic shrinkage cracking, and setting time. Those applications may have early-age strength requirements that may be addressed by the use of mixtures with low *w/cm,* and the maturity method discussed in this guide may be used to estimate in-place strength development. For such applications, 50% fly ash could be used readily. Slab type structures that are broom finished can be finished without the finishers getting on them and therefore may not be limited by increased initial setting time or trowel finishability. Low *w/cm* broom-finished slabs containing 50% fly ash have very little bleed water and may have to be handled and finished similarly to the one-pass finishing commonly recommended for high-performance concrete containing silica fume (Silica Fume Users Manual 2005). It should be kept in mind that the ACI 318 Code restricts fly ash levels to 25% for slabs that are exposed to deicing salts.

While HVFA concrete may require a low *w/cm* to satisfy early-age strength requirements, it is important that these mixtures not contain significantly higher cementitious materials contents than concrete with normal quantities of fly ash. Let us take the following example:

> Concrete A is 50% fly-ash concrete and contains 400 lb/yd$^3$ of cement and 400 lb/yd$^3$ of fly ash;
>
> Concrete B is 25% fly-ash concrete and contains 375 lb/yd$^3$ of cement and 125 lb/yd$^3$ of fly ash.

Concrete A, because of its high cementitious materials content, is unlikely to have a much lower "$CO_2$ footprint" than Concrete B, even though its fly ash content is 50% by mass of cementitious materials.

## Maturity Method

For readers who are not familiar with the maturity method, a brief summary is provided and more details can be found elsewhere (Malhotra and Carino 2004). The strength development of concrete is a function of concrete temperature and age. The maturity method is a technique to account for the combined effects of time and temperature to estimate in-place strength at early-ages. The method requires measurement of concrete temperature and age and the use of an equation (maturity function) to compute an index that accounts for time and temperature. These equations are given in ASTM Practice C1074. To use the method, it is necessary to develop the strength-maturity relationship for the specific concrete mixture. Temperature sensors are placed in the newly placed concrete at critical locations in the structure. The sensors are connected to instruments that read the temperature and calculate the cumulative maturity index. When an estimate of in-place strength is desired, the value of the in-place maturity index is read from a maturity meter and the corresponding strength is read from the strength-maturity relationship.

### Thermal analysis

When there are specific early-age strength requirements that have to be attained at specific ages, the engineer can carry out simulations of a given concrete placement to estimate the in-place temperature history. Such programs account for the heat of hydration, the geometry of the structure, presence of insulation, and ambient conditions. The calculated temperature history can be used to compute strength development as a function of age by using the strength-maturity relationship of the specific concrete mixture. This allows the engineer to evaluate whether the proposed concrete mixture is likely to provide the required early-age strength requirement. This guide refers to ConcreteWorks, a publically available computer program developed by the Concrete Durability Center at The University of Texas at Austin, as an example of a thermal analysis and in-place strength estimation program.

## Step-by-Step Approach

The following approach is suggested for those interested in the application of the maturity method to facilitate the use of optimized higher volume fly ash (HVFA) concrete mixtures while accounting for their effect on the early-age strength gain and the resulting impact on construction operations. The approach consists of three phases:

- Phase I—Develop the HVFA concrete mixture proportions and determine the strength-maturity relationship of that concrete.
- Phase II—Carry out computer simulations of the construction process to determine whether the proposed HVFA mixture will meet the early-age strength requirements under anticipated field temperature conditions.
- Phase III—Use the maturity method to estimate in-place concrete strength development during construction.

The following provides the step-by-step procedure:

1. **Identify the early-age strength requirements for the specific structural application (such as for removal of forms, application of prestressing, early opening of pavements, etc.), and identify the age at which this strength needs to be attained; for example, a requirement of 2800 psi in 72 hours.**

HVFA concrete has a slower rate of early-age strength development compared with conventional concrete and it is important that the design professional establish an appropriate early-age strength requirement for the particular application. In most situations, rather than requiring that the concrete should attain the usual default value of 70% of specified 28-day strength before the application of construction loads, it is prudent to determine the specific early-age strength level that is required based on the structural design and the anticipated loads applied at these early ages.

2. **Choose appropriate concrete ingredient materials and establish HVFA concrete mixture proportions that will achieve the required early-age strength and other performance requirements.**

*Material Selection*

Because early-age strength is critical for some applications, it is prudent to select appropriate materials that can attain the required early-age strengths. It may not be possible to use some of the suggested materials due to material availability and conflicts with other performance criteria. Choose a cement source with a higher rate of strength gain. Cements with higher alkali content have been shown to accelerate pozzolanic reactivity; however, such cements may increase the tendency for alkali-silica reactions with susceptible aggregates. Therefore ASTM C1567 must be conducted if the aggregates are susceptible to alkali-silica reaction. Fly-ash properties such as higher fineness and higher strength activity index can be used to select fly-ash sources. A high range water-reducing (HRWR) admixture that does not increase the setting time of concrete at high dosages should be used. A HRWR admixture is often necessary to attain the low *w/cm* and maintain the required workability. Some admixture suppliers are manufacturing HRWR admixtures tailored specifically for HVFA concrete mixtures that reduce the water demand significantly, increase the early-age strength, and reduce the setting time of concrete.

*w/cm Selection*

HVFA concrete mixtures, particularly those designed to attain high early-age strength, should have lower *w/cm* than conventional concretes. While a *w/cm* as low as 0.27 has been used in some applications (Sivasundaram et al. 1989) in most situations a *w/cm* of about 0.40 may be adequate. When proportioning a HVFA mixture to attain high early-age strength, a *w/cm* of 0.40 is an excellent starting point.

*Mixing Water Content*

The low *w/cm* is typically attained by decreasing the mixing water content as much as possible. The lowest value of mixing water content should be in the range of 200 to 240 lb/yd$^3$ but this depends on the characteristics of local materials (primarily aggregate size, shape, and texture). Higher water contents may be necessary for slab-type applications that require a trowel finish because finishability is an important criterion for such applications. Low water content may detract from attaining good finishability even when HRWR admixtures are used.

*Cementitious Materials Content*

The total cementitious materials content can be determined by dividing the selected mixing water content by the required *w/cm*. HVFA concrete mixtures typically have a total cementitious materials content that is higher than mixtures containing lower fly ash contents or no fly ash. Typically, the total cementitious materials contents of normal-strength ($f'_c < 6{,}000$ psi) HVFA concrete mixtures are less than 600 lb/yd$^3$ and almost always less than 700 lb/yd$^3$.

*Adjustment to Cementitious Materials Content*

The suitability of the chosen cementitious materials content can be assessed by ensuring that the *w/(c+kf)* value of the HVFA mixtures is equal to or slightly below the *w/(c+kf)* value of a control mixture that has been found to meet the performance criteria; where *k* = efficiency factor and *w, c,* and *f* are the masses of water, cement, and fly ash, respectively. The efficiency factor of fly ash can be assumed to vary from 0.25 to 0.45, which means that 1 lb of fly ash is equivalent to 0.25 to 0.40 lb of cement in terms of early-age strength development. In this project, the efficiency factor was calculated as 0.38 based on similar early-age, standard cured cylinder strengths for the control mixture without fly ash and the mixtures with 35% of the high-lime fly ash (FA-C) and with 50% of the low-lime fly ash (FA-A) (Obla et al. 2008). It may be necessary to increase slightly the total cementitious materials content of the HVFA mixture to ensure that the *w/(c+kf)* of the HVFA mixture is slightly below the *w/(c+kf)* of the control mixture.

This process for adjusting the cementitious materials content is illustrated by the following example:

a. Assume that the concrete supplier has selected appropriate local materials to produce HVFA mixtures.
b. Assume that the control mixture contains 20% fly ash with a total cementitious materials content of 550 $lb/yd^3$ and a *w/cm* of 0.50. The goal is to develop a HVFA mixture containing 50% fly ash with an early-age (2 to 4 days) strength that will match that of the control mixture.
c. Choose a *w/cm* of 0.40 as a starting point for the HVFA mixture.
d. Assume that the lowest mixing water content that can be used with local materials is 220 $lb/yd^3$. This low water content will most likely require the use of a Type F HRWR to attain the desired workability.
e. The total cementitious materials content is calculated as 220 $lb/yd^3$ / 0.40 = 550 $lb/yd^3$.
f. Assuming that k = 0.38, the calculated value of *w/(c+kf)* for the control mixture is 0.57. The calculated value of *w/(c+kf)* for the HVFA mixture is 0.58. Increasing the total cementitious materials content of the HVFA mixture to 560 $lb/yd^3$ will reduce *w/(c+kf)* to 0.57, which is the same as the control mixture.
g. The final HVFA trial mixture is as follows: Cement = 280 $lb/yd^3$, fly ash = 280 $lb/yd^3$, and water = 220 $lb/yd^3$.

The above HVFA mixture should be a reasonable starting point, even if prior information about the early-age strength development of the control concrete mixture is unavailable.

**3. Select the activation energy (AE) for strength development that most closely matches the selected cementitious materials.**

In order to determine the maturity index (equivalent age) of the concrete from its temperature history, it is necessary to use the appropriate value of the activation energy (AE). The activation energy defines the temperature dependence of early-age strength development and its value depends primarily on the cementitious materials and mixture proportions that are used. Table 1 provides the activation energies for the six mixtures tested in this project. The research team intends to increase the activation energy database in the future. Alternatively, the activation energy for the selected cementitious materials can be determined in accordance with the Annex of ASTM C1074.

In calculating the equivalent age at a reference temperature ($T_r$), such as 73ºF, an exponential equation known as the Arrhenius equation is used. The equation requires that temperature be expressed using the absolute temperature scale. So if inch-pound units are used, temperature needs to be converted to the Rankine scale (ºR) by adding 459.7 to the temperature in ºF. If SI units are used, temperature needs to be converted to the Kelvin scale (K) by adding 273.2 to the temperature in ºC. Activation energy is measured in units of energy per mole and is reported typically in SI units, that is, J/mol, where J stands for joules and "mol" stands for mole. The Arrhenius equation uses the parameter activation energy divided by the universal gas constant (R), and the quotient is often called Q. In SI units, R has a value of about 8.31 J/(K mol), where K stands for degrees Kelvin (note that the degrees symbol is not used with K). When the activation energy is divided by the gas constant, the units are K. For example, if the activation energy is 40,000 J/mol (or 40 kJ/mol), the Q value is 40,000/8.31 (K) or about 4,800 K. The Q-values for the six mixtures tested in this project are shown in Table 1. The ConcreteWorks program allows the use of inch-pound (or English) units or SI (or metric) units. Thus Q-values in units of K need to be multiplied by 1.8 to obtain the value in units of ºR. The last column of Table 1 gives the Q-values in terms of ºR.

4. **Develop the strength-maturity relationship for the selected HVFA concrete mixture following the procedure in ASTM C1074.**

To develop the strength-maturity relationship, prepare a trial batch of the HVFA concrete mixture in accordance with ASTM C192/C192M and cast a total of seventeen 4 by 8 in. concrete cylinders. The cylinders should be standard cured in a moist room immediately after they are made. Two cylinders should have embedded temperature sensors to measure concrete temperature. The sensors are connected to maturity meters or data loggers. Test three cylinders according to ASTM C39/C39M at each age of 1, 3, 7, 14, and 28 days. Temperature data should be collected every half hour or less for the first 48 hours and may be collected at more extended intervals for later ages.

The strength versus equivalent age data are fitted to an equation that will be used for estimating in-place strength in the actual structure based on measured in-place temperatures. Several equations can be used for this purpose. The ConcreteWorks program uses the following exponential equation:

$$f_c = f_{cu}\, e^{-\left(\frac{\tau}{t_e}\right)^{\beta}} \qquad (1)$$

where $f_c$ = compressive strength (psi); $t_e$ = equivalent age (hours); $f_{cu}$ (psi), τ (hours), and β are best fit parameters, which are termed the "maturity constants."

5. **Select the hydration parameters that most closely match the selected materials.**

The hydration parameters are used by the thermal analysis program to model the development of heat of hydration. Table 2 lists the hydration parameters for the six mixtures tested in this project. Alternatively, the ConcreteWorks program suggests the hydration parameters based on the cementitious materials and mixture proportions have been selected.

6. **Conduct a thermal analysis and strength development simulation using the selected HVFA concrete mixture, the appropriate member geometry, the proposed construction sequence, and the anticipated ambient temperatures. Evaluate whether the selected HVFA mixture will meet the early-age strength requirements.**

A thermal analysis computer program, such as ConcreteWorks, should be used to verify whether the selected HVFA mixture will meet the early-age strength requirements. The hydration constants and maturity constants of the mixture and construction related parameters are provided as input and the program calculates the temperature histories within the structure. Construction-related information would include the specific geometry of the structural member, the location of the structure, the date and time of the placement, and form insulation. Data on the location of the structure and when the concrete will be placed are used to access a database of likely ambient temperatures during construction. Based on the predicted temperature development and the strength-maturity relationship, the program estimates strength development at different locations in the structure. The corner of a member, where two edges meet, will generally be the coldest location and will result in the lowest strength. The center of a member will generally have the highest temperature and highest strength. For traffic opening decisions for concrete pavements, the in-place strength at the center of the pavement can be estimated. For removal of forms from columns, the estimated strength at 1 in. from the column face can be used. The strength at this location is similar to the average strength predicted by the ConcreteWorks program.

The project engineer can decide to use the HVFA mixture if the estimated in-place strengths exceed the early age strength requirements. If the requirements are not met, the HVFA concrete mixture proportions can be modified or alternative formwork insulation methods can be evaluated to increase the internal temperature and strength development. For example, it may be decided to reduce the *w/cm* by increasing the total cementitious materials content or by adding HRWR admixture, or both, as follows:

Trial B – 50% fly ash, total cementitious materials = 610 lb/yd$^3$, *w/cm* = 0.36, Type F HRWR admixture;

Trial C – 50% fly ash, total cementitious materials = 550 lb/yd$^3$, *w/cm* = 0.40, Type F HRWR admixture specially formulated for HVFA concrete that reduces setting time and enhances early-age strength gain.

If a new HVFA mixture is selected, a new strength-maturity relationship needs to be developed.

7. **Once the project starts, the engineer oversees measurement of in-place maturity in accordance with ASTM C1074 and uses the strength-maturity relationship to estimate in-place strength during construction.**

For reliable estimates of the in-place strength, the value of the activation energy and the strength-maturity relationship have to be determined for the materials and mixture proportions used in the project. However, this is not always possible, especially for small projects. At a minimum, a strength-age curve has to be developed from testing standard-cured cylinders in the laboratory (step 4). In that case, the strength versus age curve is a good approximation of the strength versus equivalent age relationship, provided the temperature of the concrete specimens is maintained within 70ºF to 76ºF.

Prior to performing critical operations, such as formwork removal or post-tensioning, strengths estimated from the maturity method have to be verified with other tests to ensure that the concrete in the structure has a potential strength that is similar to that of the concrete used to develop the strength-maturity relationship. This is because the maturity method is based on measuring only the in-place temperature, and this measurement cannot detect batching errors. When the maturity method indicates adequate in-place strength, verification tests using the pullout test can be done on the structure in accordance with ASTM C900. This would require embedding pullout inserts in the concrete during placement. Alternatively, early-age tests of field cast cylinders can be used to estimate the potential 28-day strength. This can be done in accordance with ASTM C918/C918M.

## CASE STUDIES

The following case studies are provided to illustrate the various steps involved in incorporating HVFA concrete into a construction project. The control mixture and the 50% FA-A mixture that were tested in the project (Obla et al. 2008) were evaluated in both cases.

Two columns with cross sections of 3 by 3 feet and 5 by 5 feet are used for the thermal analyses and strength development calculations performed using ConcreteWorks.

### Case Study I - Columns constructed in winter in Minneapolis, MN

#### Step 1

Based on a structural analysis, it is determined that a strength of 2250 psi is required for formwork removal. The contractor determines that for optimum construction operations the formwork has to be removed within 96 hours after casting.

#### Step 2

The control mixture has the following mixture proportions: Type I portland cement = 510 $lb/yd^3$, mixing water = 286 $lb/yd^3$, *w/cm* = 0.56, and *w/(c+kf)* = 0.56.

The 50% fly-ash mixture has the following mixture proportions: Type I portland cement = 308 $lb/yd^3$, fly ash = 298 $lb/yd^3$, mixing water=237 $lb/yd^3$, *w/cm* = 0.39, and *w/(c+kf)* = 0.56 for k = 0.38.

#### Steps 3, 4, and 5

These steps were completed as part of the research study and the details are provided in the research report. For the mixtures tested in this research project, activation energy values for the control and 50% FA-A mixtures are taken as 41.5 kJ/mol and 33.4 kJ/mol, respectively.

For the control mixture, the best-fit maturity constants that define the strength–maturity relationship were calculated as follows:

- Limiting strength, $f_{cu}$ = 10,100 psi,
- Slope parameter, $\beta$ = 0.28,
- Time parameter, $\tau$ = 340.8 hours.

For the 50% FA-A mixture, the maturity constants were calculated as follows:

- Limiting strength, $f_{cu}$ = 12,200 psi,
- Slope parameter, $\beta$ = 0.29,
- Time parameter, $\tau$ = 528 hours.

For the control mixture tested in this project, the hydration constants are as follows:

- Activation energy for hydration, E = 46.1 kJ/mol,
- Total heat of hydration = 488 J/kg,
- Slope parameter, $\beta$ = 0.785,
- Time parameter, $\tau$ = 17.8 hours,
- Ultimate degree of hydration, $\alpha_u$=0.913.

For the 50% FA-A mixture tested in this project, the hydration constants are as follows:

- E = 22.3 kJ/mol,
- Total heat of hydration = 258 J/kg,
- Slope parameter, $\beta$ = 1.1,
- Time Parameter, $\tau$ = 13.4 hours,
- Ultimate degree of hydration, $\alpha_u$ = 0.837.

**Step 6**

The forms are assumed to be of natural wood and covered with insulation with an R-value of 2.91 $in^2 \cdot hr \cdot °F/BTU$. For the purpose of the analysis, the forms are not removed for the duration of the analysis, which is carried out to 14 days. The concrete columns were simulated to be cast at 9 a.m. on January 15 and typical ambient average hourly climatic conditions for Minneapolis are selected automatically by the ConcreteWorks software program. The other default values suggested by ConcreteWorks were used.

The estimated concrete temperature versus age results from the ConcreteWorks program are summarized in Figure 1. Figure 2 shows the estimated compressive strength versus age plot for the four cases (control and 50% FA-A mixtures and two column sizes). As expected, the larger 5 by 5 ft. columns are predicted to have higher early-age in-place strengths compared with the smaller 3 by 3 ft. columns. The 5 by 5 ft. column with the control mixture showed higher early-age in-place strength compared with the same size column made with the 50% FA-A mixture. The trend however was reversed for the 3 by 3 ft. column. The 2250 psi strength level was attained at:

315 hours for 3 by 3 ft column with the control mixture
270 hours for 3 by 3 ft column with the 50% FA-A mixture
153 hours for 5 by 5 ft column with the control mixture
197 hours for 5 by 5 ft column with the 50% FA-A mixture

Clearly, due to extremely low ambient temperatures, the target early-age strength of 2250 psi at 96 hours was not attained in any of the four cases. If the 96-hour schedule is to be maintained, the concrete temperature will need to be increased by supplying concrete with a higher initial temperature and providing addition insulation or external heating. These are the typical recommendations for cold weather concreting given in ACI 306R. The ConcreteWorks program can be used to evaluate the effects of changes in these construction parameters. The use of Type III cement, lower *w/cm* mixtures, lower fly-ash contents, and accelerating chemical admixtures are other options. In these cases, appropriate values of activation energy, maturity constants, and hydration parameters would need to be determined.

**Case Study II - Columns constructed in summer in Houston, TX**

**Step 1**

Based on a structural analysis, it is determined that a strength of 2250 psi is required for formwork removal. The contractor determines that for the desired construction schedule the formwork should be removed within 48 hours after casting.

**Steps 2, 3, 4, and 5**

The details are already provided in Case Study I and the same two mixtures will be evaluated.

**Step 6**

Natural wood forms will be used, and for the purpose of the analysis they are kept in place for the duration of the analysis, which is chosen to be 7 days. The concrete columns were planned to be cast on August 15 and the typical average hourly climatic conditions for Houston are selected automatically by the ConcreteWorks software program. The other default values suggested by ConcreteWorks were used.

The concrete temperature versus age results from the ConcreteWorks program are summarized in Figure 3. Figure 4 shows the compressive strength versus age plot for the four cases (control and 50% FA-A mixtures and two different column sizes). Both column sizes with the control mixture had similar early-age in-place strengths, which were greater than the columns made with the 50% FA-A mixture. The 2250 psi strength level was attained at:

28 hours for 3 by 3 ft column with the control mixture
45 hours for 3 by 3 ft column with the 50% FA-A mixture
27 hours for 5 by 5 ft column with the control mixture
44 hours for 5 by 5 ft column with the 50% FA-A mixture

Clearly, the higher ambient temperatures helped the concrete to attain the target early-age strength of 2250 psi within 48 hours in all cases. Thus, we would conclude that this HVFA mixture should meet the construction time constraints of this project.

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## Table 1 Activation Energies for Mixtures Tested in this Project

| Mixture | Fly Ash Type | *w/cm* | Activation Energy (kJ/mol) | Q-Value (K) | Q-Value (ºR) |
|---|---|---|---|---|---|
| Control | NA | 0.56 | 41.4 | 4980 | 8960 |
| 20% FA-A | Low CaO Class F | 0.51 | 48.1 | 5790 | 10410 |
| 35% FA-A | Low CaO Class F | 0.50 | 15.6 | 1880 | 3380 |
| 50% FA-A | Low CaO Class F | 0.39 | 33.4 | 4020 | 7230 |
| 35% FA-B | Intermediate CaO Class F | 0.42 | 33.0 | 3970 | 7140 |
| 35% FA-C | High CaO Class C | 0.42 | 28.3 | 3400 | 6130 |

Low CaO refers to fly ash with CaO < 8%
Intermediate CaO refers to fly ash with CaO from 8 % to 20%
Low CaO refers to fly ash with CaO > 20%

## Table 2 Best-fit Hydration Parameters for Mixtures Testes in this Project ($T_r$ = 73 °F)

| Parameter | Mixture ID | | | | | |
|---|---|---|---|---|---|---|
| | Control | 20%FA-A | 35%FA-A | 50%FA-A | 35%FA-B | 35%FA-C |
| E-value for Hydration (kJ/mol) | 46.1 | 36.4 | 28.1 | 22.3 | 29.2 | 29.1 |
| Total Heat of Hydration (J/kg) | 488 | 394 | 314 | 258 | 401 | 464 |
| Slope Parameter, $\beta$ | 0.785 | 1.024 | 1.000 | 1.100 | 0.990 | 0.899 |
| Time Parameter, $\tau$ (hours) | 17.8 | 13.3 | 13.7 | 13.4 | 13.0 | 24.6 |
| Ultimate DOH, $\alpha_u$ | 0.913 | 0.854 | 0.770 | 0.837 | 0.579 | 0.855 |

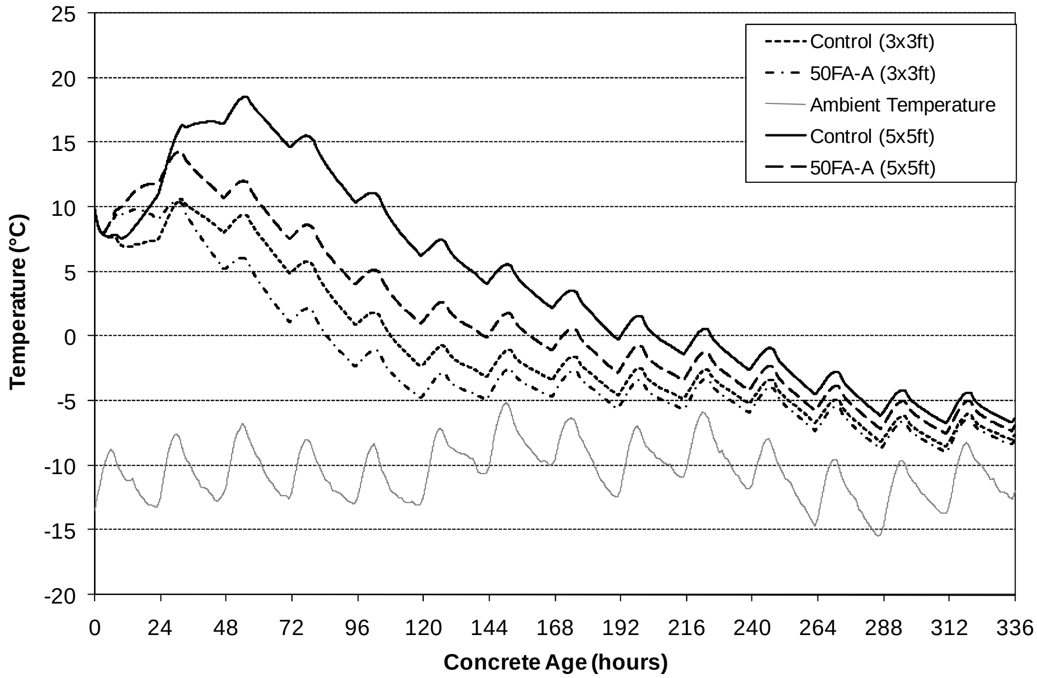


**Figure 1 Predicted Temperature Age Plot for Columns Constructed in Winter in Minneapolis**

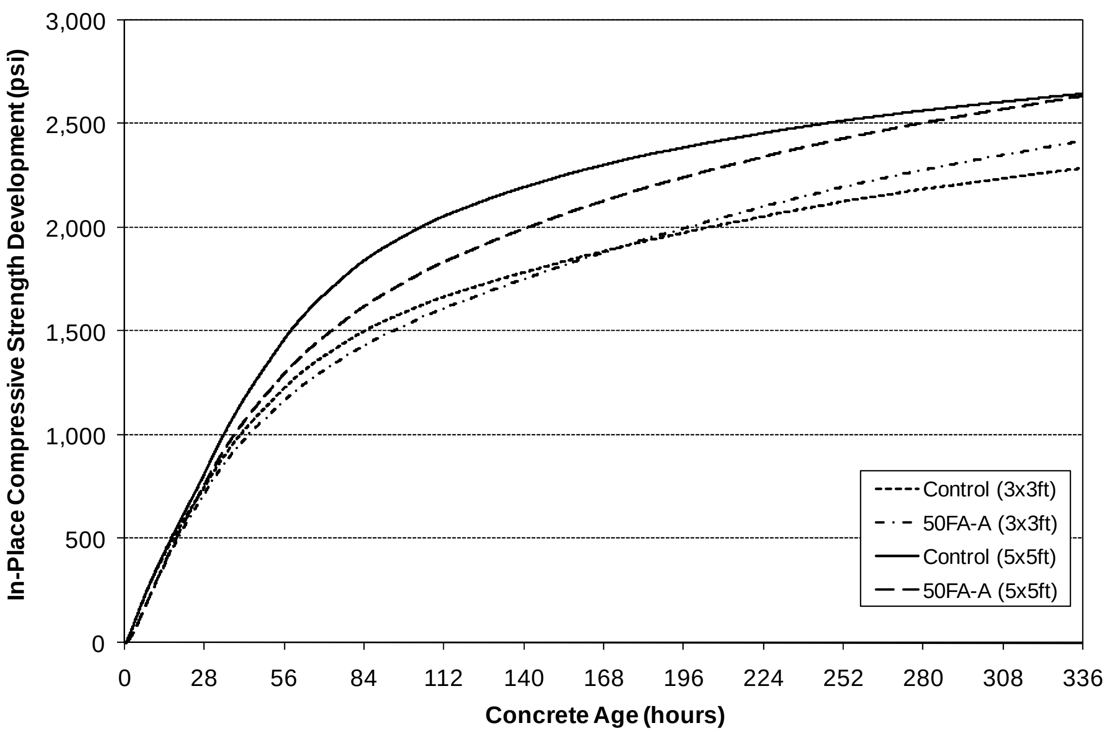


**Figure 2 Predicted Strength Age Plot for Columns Constructed in Winter in Minneapolis**

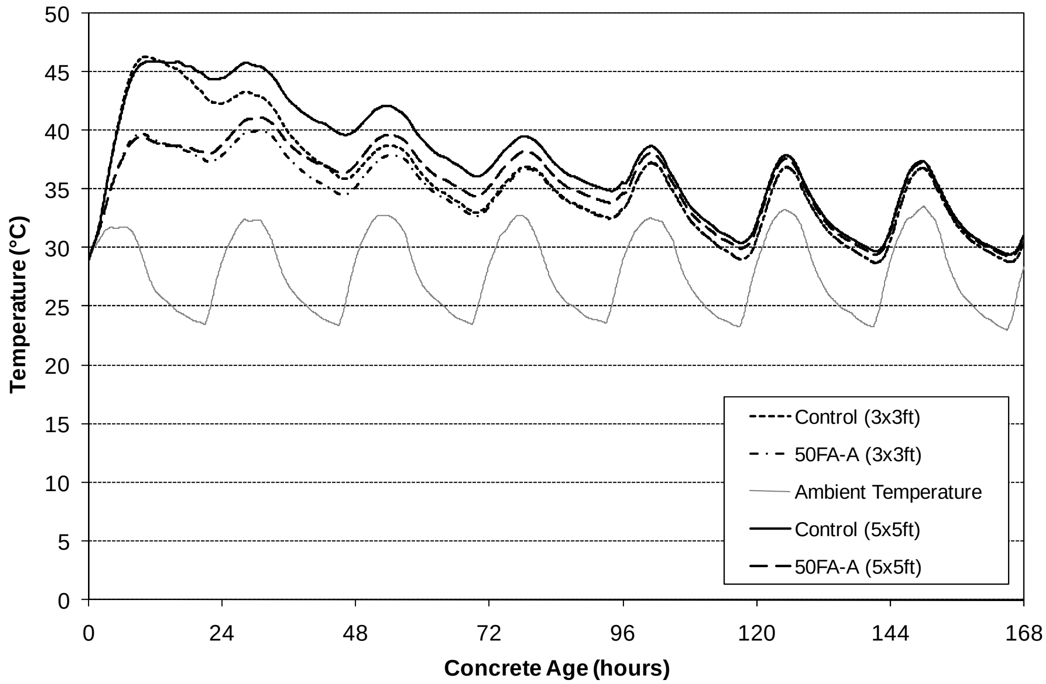


**Figure 3. Predicted Temperature Age Plot for Columns Constructed in Summer in Houston**

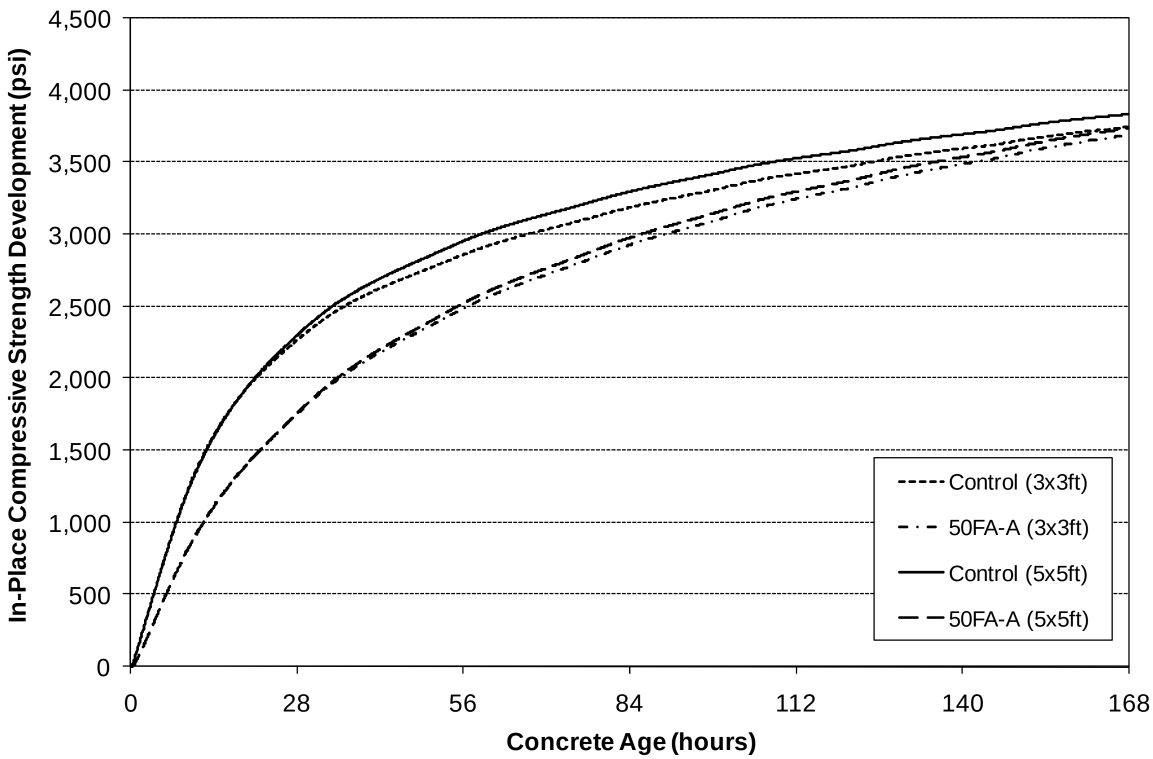


**Figure 4. Predicted Strength Age Plots for Columns Constructed in Summer in Houston**