EVALUATION OF IN PLACE STRENGTH OF HIGH-VOLUME FLY ASH CONCRETE

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Abstract

The use of fly ash in concrete has reached significant attention over the recent years due to environmental concerns regarding its disposal from one hand and significant benefits to concrete on the other, when it is used as a supplementary cementitious material. While low fly ash contents are in some cases routinely used in concrete, high volume fly ash (HVFA) concrete is not so frequently used due to perceived lower early age strengths. Objective of this study was to demonstrate using maturity based techniques that the beneficial effects of high in-place temperature may be able to compensate for the slower rate of strength gain in HVFA concrete. Furthermore, different methods (match cured cylinders, pull out testing) estimating the early-age in-place strength of HVFA concrete were examined so as to confirm the maturity predicted strengths. The results have shown that the use of standard and field cured cylinders actually penalize estimates of concrete strength in the field. Higher in place temperatures due to the mass characteristics of structural element clearly led to increased early age strengths.

Keywords: Concrete, Fly Ash, Supplementary Cementitious Materials, Maturity, Pullout Test.

1. Introduction.

Fly ash is widely used as a pozzolanic supplementary cementitious material in different concrete applications. The use of low calcium (class F) and high calcium (class C) fly ash in concrete has been studied in past projects examining potential benefits in fresh concrete properties, durability and strength development [1-4]. However, recent environmental policies and regulations concerning the disposal of by products have increased the need to use of fly ash in concrete. Past studies [3-5] have examined to some degree large amounts of replacement of cement by fly ash, up to 50% in some cases. The concrete industry is one of the largest industries to consume fly ash. However, its use in Portland cement concrete has always been limited due to concerns related to slower rate of strength gain at early ages and delayed setting times. Lower early-age strengths typically prolong form work removal times (among other) which delay construction scheduling and therefore escalate construction costs. Delayed initial setting time prolongs the time that the concrete finishing crew has to wait at the job site before final finishing of concrete slabs. This "idle" waiting time substantially increases concrete construction costs of structural elements like slabs that need to be finished. Delayed initial setting times also increase the chances of plastic shrinkage cracking.

This research project concentrated on the early strength gain development of high volume fly ash concrete, with the following objectives:

1) Evaluate the apparent activation energy for HVFA mixtures.

2) Develop the strength maturity relationship for a variety of HVFA concrete mixtures (this terminology should be consistently used throughout the paper)

3) Establish the pullout-strength relationship for a variety of HVFA concrete mixtures

4) Estimate the early-age in-place concrete strength development in mass concrete with different methods so as to demonstrate that field and standard cure cylinders do not appropriately represent actual in-place strength in mass structural elements.

2. Experimental Testing.

While this experimental field and laboratory study included a variety of fly ash types and mixtures the results from a subset of this investigation is reported herein. The following sections incorporate information on materials, mix design and testing, as well as specific results and modeling of the study.

2.1 Materials.

The overall purpose of this research was to examine a) the effects of different type of fly ash (type C and F) and HVFA contents ranging from 20% to 50% on concrete strength gain. The results related to the use of 35% Class C fly ash (CaO >20%) are reported in this paper.

The chemical composition of this fly ash and the Type I cement used in these experiments are reported in Table 1. Locally available No. 57 crushed stone coarse aggregate of 25 mm (1.0”) Nominal maximum size size was used with natural sand. A high range water reducing (HRWR) admixture was also used for meeting the target slump value.

Table 1. Chemical Properties of Cement and Class C Fly Ash

Composition	Cement	FA-C
(SiO_2), %	20.50	38.48
(Al_2O_3), %	5.00	20.64
(Fe_2O_3), %	3.30	5.46
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	28.80	64.58
(CaO), %	62.70	23.44
(MgO), %	3.80	4.10
(SO_3), %	2.90	1.69
(K_2O), %	-	0.61
LOI, %	0.85	0.27

2.2 Mixture Design.

The target concrete strength and slump properties for design were 4000 psi compressive strength and a slump within 150-200 mm (6-8 inches). The control concrete mixture had 302 kg/m^3 (510 pounds per cubic yard) of type I cement and a water to cement ratio of 0.56. To meet the target slump range 62.1ml (2.1 oz) of high range water reducer was used. The fly ash mixture was designed so that the early strengths (3, and 7 days) of the mixture is comparable to the Portland cement control mixture. This is how, in practice, the concrete producer who is concerned about early-age strengths and wants to maximize fly ash use will approach the fly ash mixture proportioning. The approach is primarily to reduce the w/cm as the fly ash percentage is increased. The w/cm reduction is achieved by a combination of increased total cementitious content and reduction in water content through the use of high-range water-reducers. In this case, the high lime Class C fly ash concrete mixture was designed with 35% replacement of Portland cement. The total cementitious material was 332 kg /m^3 (561 pounds per cubic yard) and a water to cementitious ratio of 0.42. To meet the target slump range 150.8 ml (5.1 oz) of high range water reducer was used per 45kg (100 lb) of cementitious material. Mortar cubes for activation energy evaluation were prepared based on ASTM C1074 [6]. The fine aggregate to cement ratio of the mortar mix was equal to the coarse aggregate to cement ratio for each mix as required by ASTM C 1074. The water to cement ratio and the admixtures were kept at same proportion as in each concrete mix.

2.3 Experimental testing procedures.

In order to achieve the objectives of this study the following testing was undertaken.

2.3.1 Testing Procedure for the Determination of Activation Energy and Equivalent Age.

The determination of the activation energy (AE) for the mixtures included in this research project was carried out according to the guidelines of ASTM C1074. As indicated previously, the mortar mixtures were proportioned so that the ratios of fine aggregate to cement (FA/C) were the same as the ratios of coarse aggregate to cement (CA/C) in the corresponding concrete mixtures, as recommended in Annex A1 of ASTM C 1074. Mortars were mixed and cured at 4 temperatures, 7.2°C (45°F), 21.2 °C (70°F), 37.8°C (100°F), and 48.9°C (120°F). The mortar cubes were cured in lime-saturated water baths and tested for compressive strength at 6 different ages. These ages (1, 2, 4, 7, 14, and 28 days) are equivalent ages based on curing at 23 °C (73°F). The equivalent age, t_e, is defined as the length of time at a reference temperature required to produce a maturity equal to the maturity achieved by a curing period at temperatures different from the reference temperature. This relationship is given by equation 1:

$$t_e = \sum_{0}^{t} e^{\frac{-E}{R}\left(\frac{1}{T}-\frac{1}{Tr}\right)\Delta t} \quad \textbf{(1)}$$

Where:
t_e = the equivalent age at the reference temperature,
E = apparent activation energy, J/mol,
R = universal gas constant, 8.314 J/mol-K,
T = average absolute temperature of the concrete during interval Δt, Kelvin, and
T_r = absolute reference temperature, Kelvin.

The reference temperature for the analysis was set at 23 °C (73^{O}F). Temperature data was collected every 30 minutes during the curing process of the blocks.

2.3.2 Testing Procedures for In-Place Strength, Strength- Maturity Relationship and Pullout test Correlation.

In addition to the standardized laboratory compressive strength evaluation and field – cured cylinders, pullout testing and a sure cure system was used in order to carry out the experimental work of the study.

Pullout testing was performed on field concrete blocks and lab cubes as indicated above at specific days during the early ages of concrete strength gain. Pullout testing is a non destructive testing method used during construction to measure the force required to pull out an insert from the concrete mass. This insert has an enlarged head 2.5cm (1 inch) in diameter and it is placed 2.5cm (1 inch) deep into the concrete from the surface. The insert is pulled centrally against a 5.5cm (2.16) inch diameter counter pressure disc on the surface. The concrete between the enlarged head and the counter pressure disc is compressed. Thus, the pull out load is a direct measure of the compressive strength and can be related to different uniaxial strength properties of concrete.

For larger concrete structural elements, (mass structure members) it is expected to have a faster rate of reaction for concrete, and thus faster strength gain at early ages. Thus, field cured concrete cylinders are not expected to provide reliable estimation of the in-place compressive strength. For this reason a sure cure system was used that may provide more reliable field strength estimates since it simulates the curing temperature based on the temperature history of mass concrete in the structure. Sure cure is a curing system used to monitor field temperature of concrete in the structure and then control the temperature of concrete in the match cure cylinder molds. The Sure Cure system consists of a micro-controller, the match cure cylinders, and a T type thermocouple. The micro controller is coupled with software that monitors the field temperature and consecutively replicates this temperature on the molds. In other words, the concrete in the match cure molds is exposed to the same time-temperature history as the field structural elements. Thus the match-cured specimens may be considered as the best estimate of the true in-place strength.

In order to monitor strength gain with time and relate the results to temperature time history the following testing was conducted for each mixture:

1. Twenty standard cure cylinders were prepared and tested at 1, 2, 4, 7, 14, and 28 days for compressive strength with three replicates.

2. Ten field cure and eight match cure cylinders, were casted and tested for compressive strength at 2, 4, and 7 days, with three and two replicates respectively, at each age.

3. Field blocks were instrumented with pullout inserts at different locations. A block of 0.6mx0.6mx1.8m (2ft X 2 ft. X 6ft) was prepared for each mixture with 24 pullout inserts placed on the two longer faces of the block (i.e., 12 insert on each side) and at equal distances. These data were used for monitoring pull out force, and thus strength gain, at different ages.

4. Twelve 20.3cmx20.3cm (8 inch x 8 inch) concrete cubes were prepared for laboratory pullout testing. These cubes were used for establishing the relationship between pullout force and compressive strength. Each cube had four inserts, one on each face, except top and bottom. Two cubes were tested for pullout load at each age (1, 2, 4, 7, 14, 28 days).

5. Temperature was monitored using temperature sensors (iButtons) at a variety of locations. Specifically, eight temperature sensors were placed at most critical section locations to capture the temperature gradient within the block.

6. Match cure cylinders were used to replicate the same temperature history of the block with the use of a sure cure system. The compressive strength of these cylinders was evaluated so as to assess their ability to accurately predict field concrete strength of the blocks.

2.3.3 Maturity Modeling.

The temperature-time history of concrete is used in the maturity concept to predict the compressive strength. The principle behind maturity modeling is based on the theory of physical chemistry. Two basic parameters are primarily used, the rate constant and the activation energy. Two modeling approaches have been historically used, the Nurse-Saul [7] and the equivalent age based on Arrhenius equation [8-10]. In the first case, a linear mathematical equation is used for predicting maturity by considering the sum of the product temperature and time as concrete hardens and gains strength. This approach considers that maturity is independent of the specific characteristics of the time-temperature history but is related to the sum of this product.

In concrete maturity modeling, the equivalent age concept has been proposed where actual time temperature history is converted to isothermal curing condition at a reference temperature. Equivalent age modeling is based on the Arrhenius equation of chemical rate reaction. The activation energy is evaluated according to ASTM C1074 by measuring the strength development of mortar mixtures. Carino (1984) [9] has proposed a hyperbolic function for strength gain under isothermal curing up to equivalent ages 28 days. The hyperbolic curve is fitted to the mortar cube strength results to get the following parameters, limiting strength (S_u) initial time for strength gain (t_o), and rate constant (k_t). This curve is fitted so as to minimize the standard error for all the constants. The natural logarithm of rate constant is plotted as a function of the inverse of curing temperature in Kelvin. This curve helps in predicting the activation energy, which is then used to calculate the equivalent age for the respective mixtures. For this study the results of the 35% class C fly ash concrete are shown in the subsequent sections.

3. Test Results

3.1 Determination of Activation Energy and Strength-Maturity Relationship.

The determination of the activation energy (AE) for the mixtures included in this research project was carried out using the hyperbolic equation as outlined in ASTM C1074. Figure 1 shows the linear relationship between the natural logarithm of rate constant for the 35% class C fly ash and the inverse of absolute temperature. The rate constant was calculated for four curing temperatures, 7.2°C (45°F), 21.2 °C (70°F), 37.8°C (100°F), and 48.9°C (120°F). The slope of the linear regression (Q) is the ratio between activation energy and universal gas constant (R=8.314 kJ/mol). The calculated activation energy for this mix was equal to 35.5 kJ/mol.

As it was indicated, the reference temperature for the analysis was set at 23 °C (73°F). Temperature data was collected every 30 minutes during the curing process of the blocks. Figure 2 shows the plot between compressive strength and equivalent age at the reference temperature. The first data point in the graph is fixed equal to the final setting time. This point is defined as the time in which strength gain in concrete starts. For 35% class C fly ash concrete mix this time period was 0.41 days, computed based on the final setting time.

As it was indicated previously, the equivalent age converts the actual time temperature history to an isothermal curing condition at the reference temperature. Since a structure has a varying temperature history during the curing process it is important to be able to predict in a reliable manner concrete strength so as to schedule any follow up construction process. To achieve this, it will be enough to monitor the actual time temperature of the concrete in the structure and use the equivalent age relationship to predict field strength at any time. Cleary this relationship is valid only for the specific mixture that was developed and thus should be determined for any other concrete mixture of interest to properly predict concrete strength. Thus, the relationship of Figure 2 should be specifically used for the 35% Class C Fly Ash concrete mix.

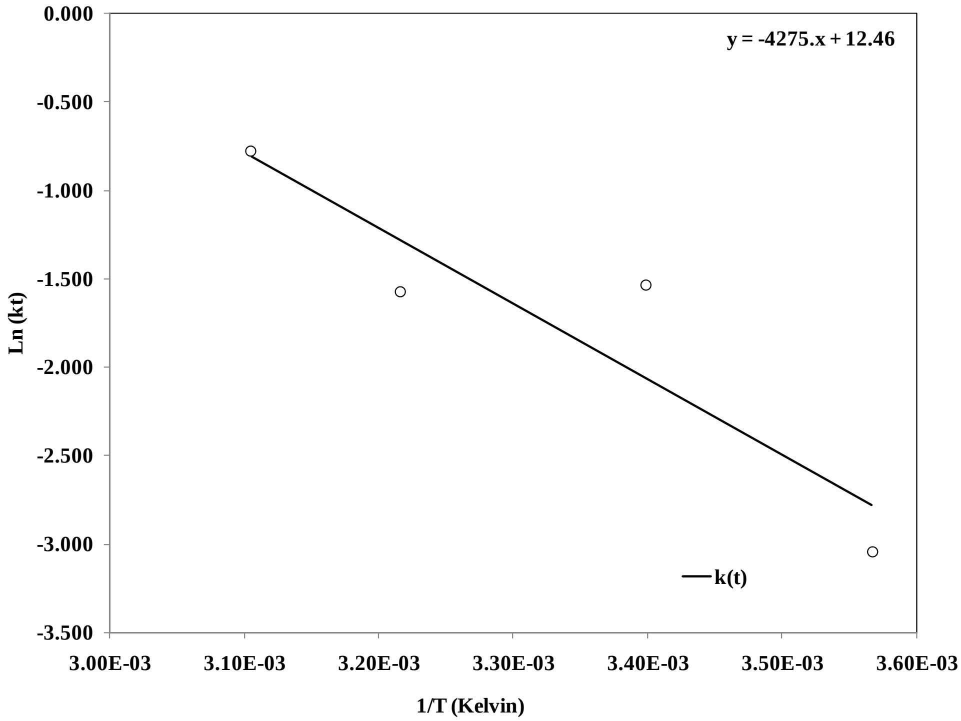

Figure 1 Arrhenius Plot for Activation Energy for the 35% Class C Fly Ash Concrete

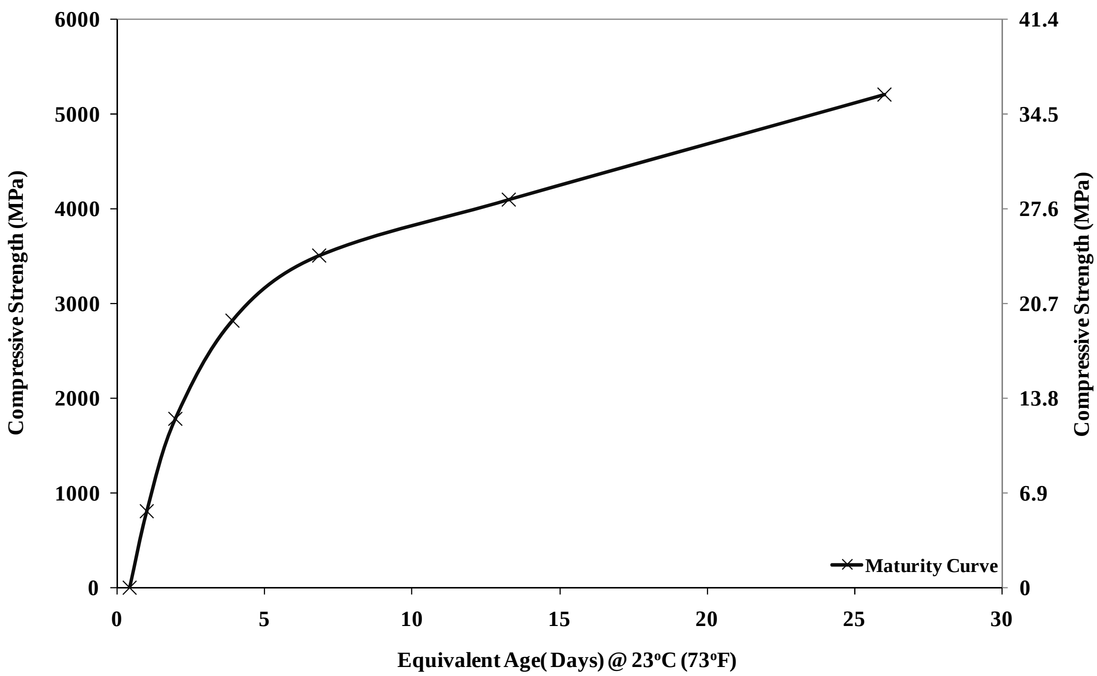

Figure 2 Equivalent Age at 23 °C (73°F) for the 35% Class C Fly Ash Concrete

3.2 Relationship Between Pullout Force and Compressive Strength.

In assessing actual field strength of structures often a non destructive method is used. Pullout testing is one of the non-destructive testing which can be used to assess concrete strength. In this research the relationship between pullout force performed on standard-cured concrete cubes and compressive strength on standard-cured cylinders was established for the mixtures of this study. Table 2 shows the average pullout load test results performed on 20.3cm (8 inch) concrete cubes tested at six different ages with eight replicates in each case. As it can be observed from these results the testing variability was within the expected range for such test as supported by previous studies.

Regression analysis was then performed between the average pullout force values and the average compressive strength values. The relationship for the 35% class C fly ash concrete is shown in Figure 3. The resulting model has a power function, equation 2, with an R^2 value of 99.4%.

$$C = 0.58 \times P^{1.22} \qquad \textbf{(2)}$$

where

C = compressive strength (MPa)
P = pullout load (kN)

This relationship is helpful in estimating the in-place compressive strength of the structure during construction when a mixture and materials similar to the one used in this study is considered.

Since it is expected that variations in time – temperature history will affect the rate of hydration and thus strength gain it was the objective of this study to examine the variability of the pullout results when inserts from a variety of locations were considered. In the experiments undertaken in this study one side of the concrete blocks with the pullout inserts was exposed to the north direction while the other side to the south. Thus, the south side of the blocks was exposed to solar radiation during the day while the north side of the block was not. However in the experiments the blocks were insulated with curing blankets to minimize such effects and significant variation in temperature and humidity between the various concrete block locations. To assess the effectiveness of such insulation pullout testing data from both sides were compared. Table 3 shows the average pullout test data values obtained from random locations of the two sides of the concrete block for the 35% class C fly ash concrete. Statistical analysis on the average pullout load values for the two faces of the block was conducted using the T-test for examining if the mean compressive strength values for the two sides of the block were significantly different from each other. A confidence level of 5% was used in the analysis, Table 4. The critical t value, equal to 2.085, is higher than the calculated t value from the experimental data. Thus, it was concluded that there is not a significant difference between the average pullout values between the two block faces. However, care should be taken during pullout test regarding the orientation of the structural element and the location of the inserts since a single element might haves different properties within its cross section due to concrete segregation and eventually temperature differential.

Table 2 Average Pullout Load for Standard Cure Cubes of 35% Class C Fly Ash Concrete

Age (Days)	Pullout Load (kN) , (COV %)
1	7.16 (14.08%)
2	12.86 (11.07%)
4	18.30 (8.76%)
7	20.84 (4.22%)
14	22.49 (6.17%)
28	30.28 (7.18%)

Table 3 Average Pullout Load on Two Faces of the Block of 35% Class C Fly Ash Concrete

Age (Days)	North (kN)	South (kN)
2	20.075	20.625
4	23.425	22.55
7	24.8	23.75

Table 4 Statistical Analysis on Pullout Load Values of the 35% Class C Fly Ash Concrete Block

	South	North
Mean	22.308	22.766
Variance	4.448	7.747
Observations	12	12
Hypothesized Mean Difference	0	
df	20	
t Stat	-0.454	
P(T<=t) one-tail	0.3271	
t Critical one-tail	1.724	
P(T<=t) two-tail	0.654	
t Critical two-tail	2.085	

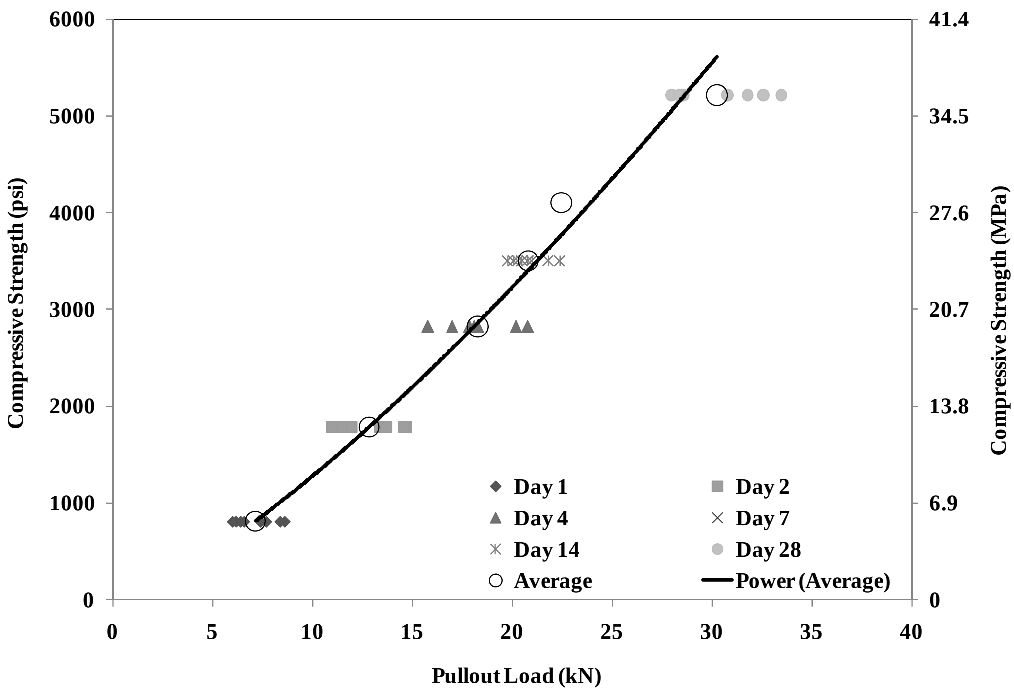

Figure 3 Compressive Strength vs. Pullout load for 35% Class C Fly Ash Concrete

3.3 Temperature Histories of Concrete and Effects of In–Place Strength.

As it was indicated, in order to evaluate the effects of different curing conditions on the strength development of concrete mixtures cylinders were cured in the lab, in the field, and in match cure conditions. Taking as an example the compressive strength results for the 35% class C fly ash concrete, presented in Figures 4 through 7, it can be observed that the match cure cylinder strength is systematically higher compared to the field cure and standard cure cylinders. This was observed for all the mixtures incorporated in this study and reflects the different thermal history for all three curing conditions. In this specific case, Figure 5, the match cure cylinders were exposed at a high temperature of around 43.3 ^{O}C (110^{O}F) within 24 hours compared to the standard cure and field cure cylinders that had a high temperature of around 21.2 °C (70°F) and 26.7 °C (80^{O}F) respectively. Higher temperature means faster reaction rate and thus faster the strength gain at early temperatures. Thus, these comparative experiments conclude that compressive strength measured using field or standard cure do not represent accurate evaluation and thus predictions of field compressive strength of structural concrete elements. In the specific case of the 35% class C fly ash concrete the 7 day compressive strength according to the match cure conditions, Figure 6, was 40% higher compared to both field and match cure compressive strength.

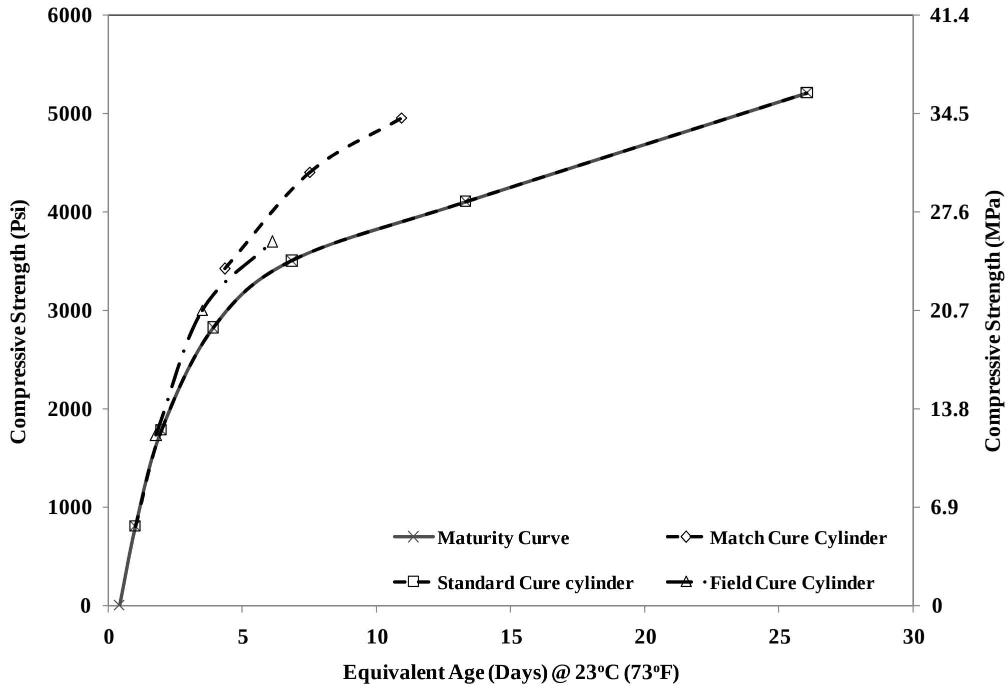

Figure 4 Compressive Strength Results for Different Curing Conditions

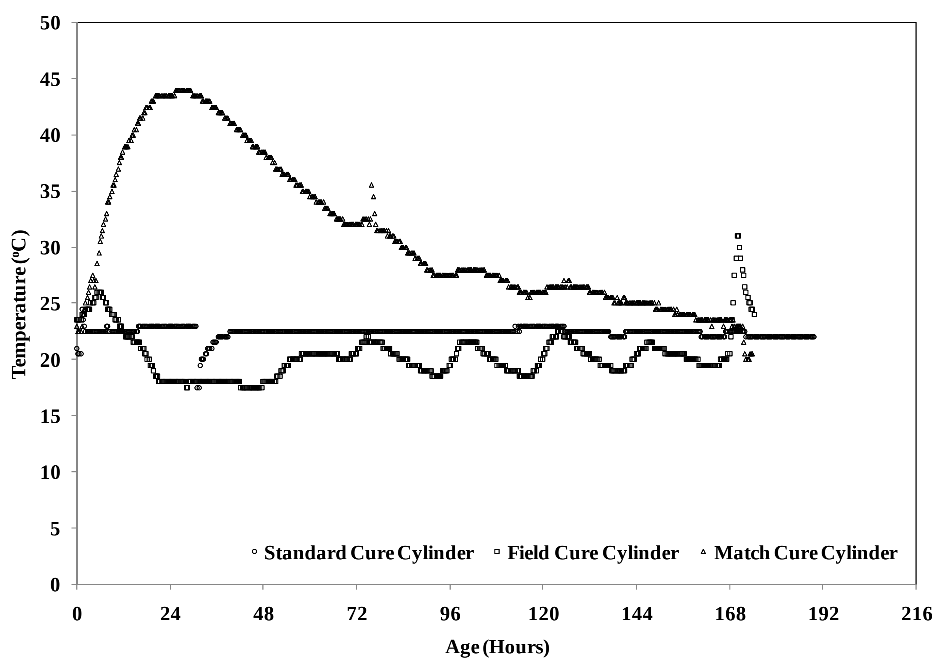

Figure 5. Thermal History of Concrete Cylinders for 35% Class C Fly Ash Concrete

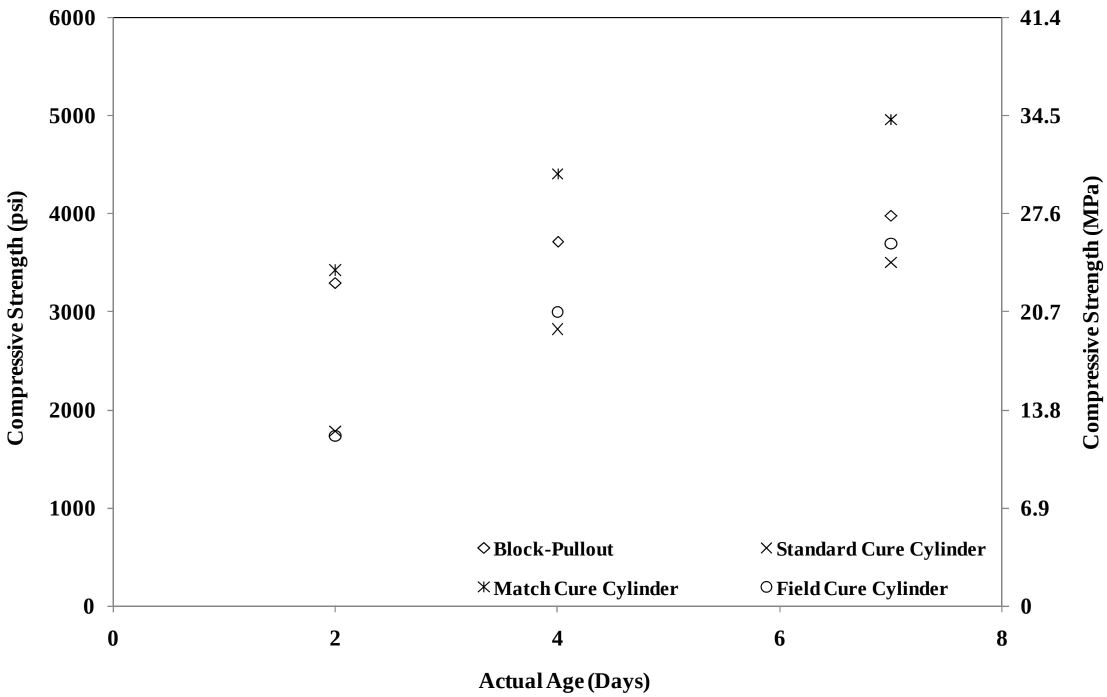

Figure 6 Compressive Strength Results from Concrete Cylinders and Pullout Test Results of the 35% Class C Fly Ash Concrete.

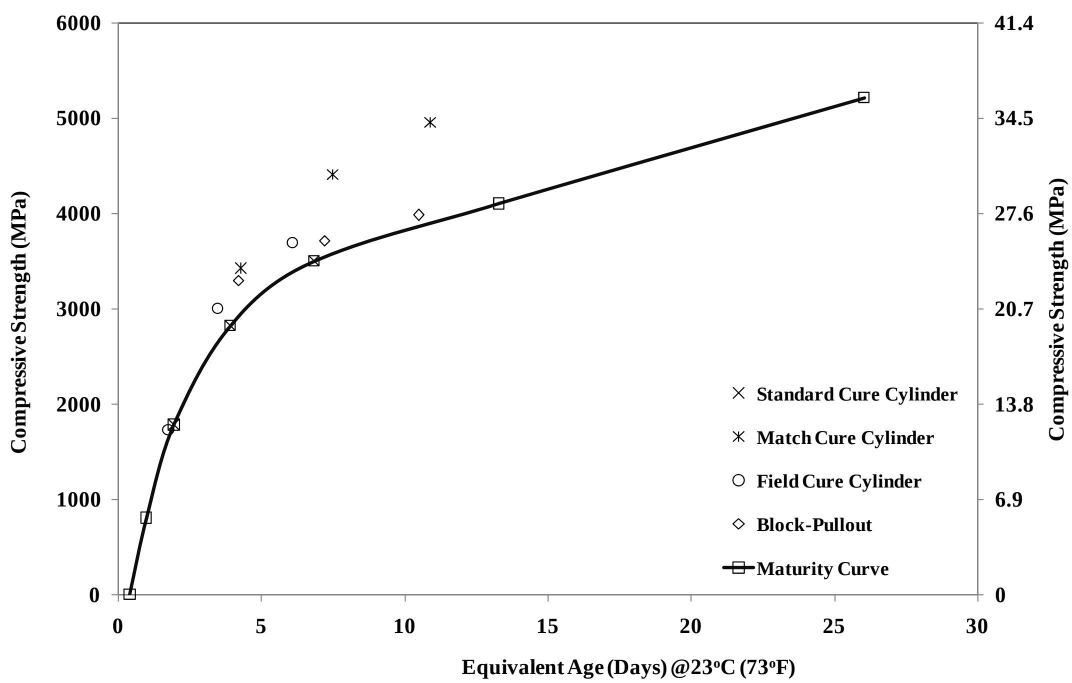

Figure 7 Compressive Strength Results versus Equivalent Age for the 35% Class C Fly Ash Concrete.

Once the relationship between pullout force and compressive strength was established for the concrete mixtures, the data of Figure 4 were complemented with the strength values from the pullout block values and using equation 2. Figure 7 shows the relationships between compressive strength and curing age for the 35% class C fly ash concrete for strength values obtained with standard and match cure cylinders, field cure cylinders, and the block pullout data in conjunction with equation 1. As it can be observed from the Figure the match cure strength is always higher, compressive strength estimated from pullout load have the second highest strength values compared to standard and field cure compressive strength, which turns out having similar values. Thus these results reconfirm that the match cure strength result provide better estimates of pullout test strength at very early ages than the other methods.

4. Conclusions.

This investigation examined the effects of HVFA in concrete using the maturity method. Objective of the investigation was to assess current methods of estimating compressive strength in the field and recommend a reliable approach of compressive strength evaluation during the construction process. The following conclusions were obtained from the analysis:

1) Compressive strength calculated based on field cure and standard cure cylinders does not provide reliable field strength values of concrete structure. To this regard, match cure cylinders better reflect the actual field in-place strength.

2) In place strengths have been predicted using maturity and pullout test procedures – mention how close was this to match cured strengths as opposed to std and field cured. Both procedures have to be developed for each particular concrete mixture and and ingredients.

3) The strength gain in concrete structure is dependent on the mass of the structure. At early ages larger structural elements will provide faster strength gain due to high-in place temperatures. This effect will accelerate the rate of hydration and thus will compensate for the slower rate of reaction associated with HVFA concrete.

4) Temperature of concrete elements should be measured at critical locations within a structure since different temperature gradient may be observed in relation to the specific location and ambient environment as well as structure exposure to solar radiation, affecting thus strength gain. For small and well insulated structural members as the one considered in this study such effects may be insignificant.

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