Maturity-Based Field Strength Predictions of Sustainable Concrete Using High-Volume Fly Ash as Supplementary Cementitious Material

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Abstract: The use of fly ash in concrete has received significant attention during recent years, owing to environmental concerns regarding its disposal and to its potential use as a supplementary cementitious material owing to its ability to improve concrete performance. Although a fly ash content of less than 25% of the total cementitious content is routinely used in concrete, high-volume fly ash (HVFA) concrete is not commonly used because of perceived lower early age strengths. The objective of this research was to use maturity based modeling to demonstrate that the beneficial effects of high temperatures observed in structural elements such as slabs and concrete beams during the hydration process associated with the mass features of such elements may compensate for the slower rate of strength gain of fly ash concrete that is typically observed in standard laboratory cured cylinders. Match cured cylinders were used during this process to estimate the early age in-place strength of HVFA concrete and to confirm the predicted mature strengths. The results have shown that standard and field cured cylinder strengths underestimate the in-place concrete strength. High in-place temperatures owing to the mass characteristics of structural elements result in increased and satisfactory in-place early age strengths for construction, measured by match cured cylinders and pullout testing, and predicted by maturity modeling. **DOI: 10.1061/(ASCE)MT.1943-5533.0001123.** © *2014 American Society of Civil Engineers.*

Introduction

After water, concrete is the most frequently used material in the world, with an estimated yearly production of 27 billion t worldwide. In the complex interaction between humanity and the environment, sustainability (i.e., the interaction between social and economic activities) and the use of sustainable materials have become increasingly important for enhancing resilience, defined by the Concrete Joint Sustainability Initiative (CJSI 2009) as “the community’s capacity to provide viable continued use in the built environment through extended service life, and adaptive re-use.”

Concrete has a significant role in the sustainable environment. Historically, cement production has contributed approximately 5% of total CO_2 emissions and 3% of greenhouse gases (Jeffries 2009). The concrete industry has adopted significant steps toward reducing emissions and greenhouse gases. Furthermore, concrete is considered to be a sustainable building material because byproducts such as fly ash, slag cements, and silica fume are regularly used; a durable and long lasting material; has the ability to absorb and retain heat, reducing energy demand for buildings; better reflects solar radiation owing to its light color reflectivity; and has the ability to filter contaminants to groundwater when used in pervious applications; additionally, and with current concrete recyclability trends, there is minimal landfilling (Balogh 2013).

In 2012, 52 million t of fly ash were produced from the burning of coal in power plants [American Coal Ash Association (ACAA) 2012]. According to the ACAA, 45% of fly ash is currently beneficially utilized in various applications, with the remaining portion disposed typically in landfills. Approximately 61% of the beneficial fly ash was used in cement and concrete applications. Because ready mixed concrete represents the single largest market for fly ash, it can offer the largest potential for increased utilization of fly ash. According to the National Ready Mix Concrete Association (NRMCA), the estimated production of ready mixed concrete in the U.S. in 2012 was 220 million m^3 (290 million yd^3). According to the NRMCA (Obla et al. 2012b), the average fly ash use in ready mixed concrete is 49 kg/m^3 (83 lb/yd^3). The survey reported that an extra 14 M tons of fly ash can be used every year in ready mixed concrete, which represents an increase in fly ash utilization of 71%, assuming the same production level as in 2012.

The objective of this research was to use maturity based modeling to demonstrate that the beneficial effects of high in-place hydration effects observed in structural elements may compensate for the slower rate in the strength gain of fly ash concrete that is typically observed in standard laboratory cured cylinders. The in-place strength of concrete in structures can be determined by monitoring the temperature–time history and estimating the in-place strength from precalibrated strength/maturity models. Maturity predictions are well established for conventional portland cement concrete, but not for high-volume fly ash (HVFA) concrete mixtures containing chemical admixtures. The Arrhenius and Nurse-Saul maturity functions are commonly used to establish the maturity index. The Arrhenius maturity function, which is considered to be more accurate (Carino 2004), was used in this research. This function requires the use of mixture-specific activation energy values for predictions of strength. The activation energy quantifies the temperature sensitivity of the concrete mixture.

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Arrhenius Maturity Function

It has been well documented that the strength of well-cured and consolidated concrete is a function of its age and curing temperature (Nurse 1949; Saul 1951; Tank and Carino 1991; Carino and Tank 1992). The effects of time and temperature can be combined into one function designated maturity, which is related to concrete strength gain. Since the first definition of maturity, many other functions have been developed and proposed. Freiesleben Hansen and Pedersen (1977) suggested another maturity function based on the concept of the Arrhenius equation. The Arrhenius equation defines the chemical reaction between two reactants and is a function of activation energy and reaction temperature. The activation energy is defined as the minimum energy necessary for a specific chemical reaction to occur. Experimental studies have confirmed that the Arrhenius approach more appropriately represents the time-temperature dependence of concrete (Carino 2004; Upadhyaya et al. 2007).

Eq. (1) represents the Arrhenius maturity function that is used to compute the maturity index in terms of equivalent age. Equivalent age represents the duration of the curing period at the reference temperature that results in the same maturity when the concrete is cured at any other temperature. The exponential part of the maturity function is an age conversion factor used to convert the actual temperature history to the temperature history at the reference temperature. The reference temperature values that have been used in Europe and the U.S. are 20°C (68°F) and 23°C (73°F), respectively:

$$t_e = \sum_0^t e^{\frac{-E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \times \Delta t \qquad (1)$$

where t_e = equivalent age at the reference temperature (h); 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 (K); T_r = absolute reference temperature (K); and Δt is the time interval (hours or days).

The activation energy is mixture specific and must be established for a specific concrete mixture prior to using the Arrhenius maturity function for estimating in-place strengths. The equivalent age function for maturity predictions was used in this research because it better captures the nonlinear effects of temperature on the rate of strength development (Carino 2004).

Experimental Testing

The study incorporated both laboratory and field testing. The laboratory study included concrete testing to develop a concrete strength/maturity relationship and mortar testing to develop activation energy. Field testing was conducted to confirm whether the in-place strengths of the HVFA concrete mixtures were higher than those estimated by cylinders. Field testing was conducted to simulate a typical concrete block and a concrete pavement slab. The following sections provide information on materials, mix design and testing, and the specific results and modeling of the study.

Materials and Instrumentation

The chemical composition of the fly ash meeting ASTM C618 (2012a) and the Type I cement meeting ASTM C150 (2012b) used in these experiments are reported in Table 1. Locally available No. 57 crushed stone coarse aggregate of 25 mm (1.0 in.) nominal maximum size was used with a natural sand, both of which met ASTM C33 (2013a). The physical and chemical properties of the materials are presented in Tables 1 and 2. A high range water reducing (HRWR) admixture was also used for meeting the target concrete slump value. Table 2 lists the measured physical properties of the fine and coarse aggregates. The relative density (specific gravity) and absorption of coarse and fine aggregates were measured in accordance with ASTM C127 and C128 (2012c), respectively; sieve analysis of both aggregates was measured in accordance with ASTM C136 (2006), and the bulk density (dry rodded unit weight) of the coarse aggregate was measured in accordance with ASTM C29/C29M (2009).

Table 1. Chemical and Physical Properties of Cement and Class F Fly Ash

Component/property	Cement	FA
Silicon dioxide (SiO_2) (%)	20.50	59.40
Aluminum dioxide (Al_2O_3) (%)	5.00	30.30
Iron oxide (Fe_2O_3) (%)	3.30	2.80
Sum of SiO_2, Al_2O_3, Fe_2O_3 (%)	28.80	92.50
Calcium oxide (CaO) (%)	62.70	1.00
Magnesium (MgO) (%)	3.80	—
Sulfur trioxide (SO_3) (%)	2.90	0.10
Potassium oxide (K_2O) (%)	—	0.64
C_3S (%)	53	—
C_2S (%)	19	—
C_3A (%)	8	—
C_4AF (%)	10	—
Loss of ignition (%)	0.85	1.30
Fineness (Blaine, m^2/kg)	368	380

iButton temperature sensors, with an accuracy of ±0.5°C, were used for field and lab testing to record the temperature–time history of the mortars and concrete mixtures at 10-min intervals during the hydration period. A wire was soldered to both ends of the iButtons to allow for interface with a computer using an RJ-11 connector; they were coated with plastic dip to protect against moisture exposure. Thus, the instrumentation used in this study and the recording time interval complied with the ASTM C1074 (ASTM 2004) requirements (i.e., recording time interval must be 0.5 h or less for the first 48 and 1 h or less thereafter; accuracy of temperature recording devices must be within ±1°C). The iButton has an internal data logger, and the stored time–temperature data were transferred from the iButtons to a PC. A match cure system was also used to cure the concrete cylinders at the same temperature history experienced by a concrete structure in the field. This system consists of a microcontroller, curing cylinders with heating coils, and a thermocouple. The accuracy of the match cure system was ±0.5°C and it was able to control curing temperatures within 1°C.

Mixture Proportions

The target design concrete strength and slump properties were 28 MPa (4,000 psi) compressive strength and a slump within 150–200 mm (6–8 in.). Table 3 provides the mix design for the 35% fly ash (FA) and 50% FA mixtures. The water to cement ratios

Table 2. Gradation and Aggregate Properties

Property	Coarse aggregate (Number 57)	Fine aggregate
Fineness modulus	—	2.73
Specific gravity [surface saturated dry (SSD)]	2.84	2.59
Absorption (%)	0.3	1.3
Dry rodded unit weight [kg/m^3 (lb/ft^3)]	1,700 (106)	N/A

Table 3. Concrete Mixture Proportions

Item	35% FA	50% FA
Cement [kg/m^3 (lb/yd^3)]	196 (331)	183 (308)
Fly ash [kg/m^3 (lb/yd^3)]	116 (196)	177 (298)
Coarse aggregate [kg/m^3 (lb/yd^3)]	1,160 (1,956)	1,167 (1,967)
Fine aggregate [kg/m^3 (lb/yd^3)]	752 (1,268)	769 (1,297)
Water [kg/m^3 (lb/yd^3)]	157 (265)	141 (237)
HRWR admixture [mL/100 kg (oz/100 lb)]	203 (5.3)	234 (6.0)
w/cm	0.50	0.39

were 0.39 for the 50% FA and 0.50 for the 35% FA mixtures. To meet the target slump values, a high-range water reducer was used in proportioning, as shown in Table 3. The FA mixtures were designed so that the early strength (three and seven days) of the mixtures was comparable to that of the control portland cement mixture. This was ensured by reducing the water to cementitious material ratio (w/cm) as the fly ash percentage was increased. The reduction in w/cm was achieved by a combination of (1) increasing the total cementitious content and (2) reducing the water content through the use of high-range water reducers.

To quantify the activation energy for the concrete mixtures considered in this study, mortar mixtures were used. The mortar mixtures were proportioned so that the fine aggregate-to-cementitious material ratio (by mass) was the same as the coarse aggregate-to-cementitious material ratio of the concrete mixtures under investigation. This is consistent with the recommendations in Annex A1 of ASTM C1074 (ASTM 2004). Table 4 provides the mortar mix proportions.

Laboratory Testing

The activation energy (AE) of the mixtures was determined according to ASTM C1074 (ASTM 2004). The mortars were mixed and cured at four temperatures: 7°C (45°F), 21°C (70°F), 38°C (100°F), and 49°C (120°F). The mortar cubes were cured in lime-saturated water baths and tested for compressive strength at six different ages. These ages (one, two, four, seven, 14, and 28 days) represented equivalent ages based on curing at 23°C (70°F) in accordance with ASTM C109/109M (2013b).

Field Testing

Field testing was conducted when the ambient temperature ranged from 10.0°C (50°F) to 12.8°C (55°F). Match cured, standard cured, and field cured compressive strengths and pullout tests were evaluated as a part of the field testing, Table 7. Details are as follows:

Table 4. Mortar Proportions

Item	20% FA	35% FA	50% FA
Cement [kg/m^3 (lb/yd^3)]	388 (654)	298 (501)	275 (464)
Fly ash [kg/m^3 (lb/yd^3)]	95 (160)	178 (299)	267 (450)
Fine aggregate [kg/m^3 (lb/yd^3)]	1,778 (2,996)	1,770 (2,983)	1,759 (2,967)
Water [kg/m^3 (lb/yd^3)]	245 (413)	240 (405)	212 (357)
HRWR admixture [mL/100 kg (oz/100 lb)]	315 (8.1)	310 (8.0)	353 (9.1)
w/cm	0.50	0.50	0.39

- Ten field cure and eight match cure cylinders were cast and tested for compressive strength at two, four, and seven days, with three and two replicates, respectively, at each age in accordance with ASTM C39/39M (2014).
- Concrete blocks with dimensions of $0.6 \times 0.6 \times 1.8$ m ($2 \times 2 \times 6$ ft) were prepared and their temperature was monitored by using the temperature sensors at a variety of locations. Specifically, eight temperature sensors were placed at most critical locations to capture the temperature gradient within each block. Pullout inserts were also included for estimating the in-place strength by using correlations between pullout force and strength.
- A slab with dimensions of $2.4 \times 2.4 \times 0.34$ m ($8 \times 8 \times 0.58$ ft) was prepared for the 50% FA content mixture and the temperature was monitored by using temperature sensors at a variety of locations. Specifically, five temperature sensors were placed at most critical section locations to indicate the temperature gradient within the block.
- 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.

Activation Energy

AE was calculated in accordance with ASTM C1074 (ASTM 2004) Annex A1, and determined by using strength age data for three mixtures. After the strength data for the mixtures were obtained, strength was plotted as a function of curing age for each curing temperature. In ASTM C1074 (ASTM 2004) a hyperbolic model, Eq. (2), is suggested to characterize the compressive strength–age relationship. In this approach, t_0 was substituted with the final setting time measured for each batch of mortar:

$$S(t) = S_u(t)\frac{k(T) \times (t - t_{fs})}{1 + k(T) \times (t - t_{fs})} \quad (2)$$

where $S(t)$ = compressive strength [MPa (psi)]; $S_u(t)$ = limiting strength [MPa (psi)]; $k(T)$ = rate constant (1/days); t = testing age (days); and t_{fs} = final setting time (days). Least-squares regression analysis was used to determine the best fitting values for S_u and $k(T)$. Fig. 1 shows an example of the graphical representation of rate constant versus curing temperature for the 50% FA–asphalt

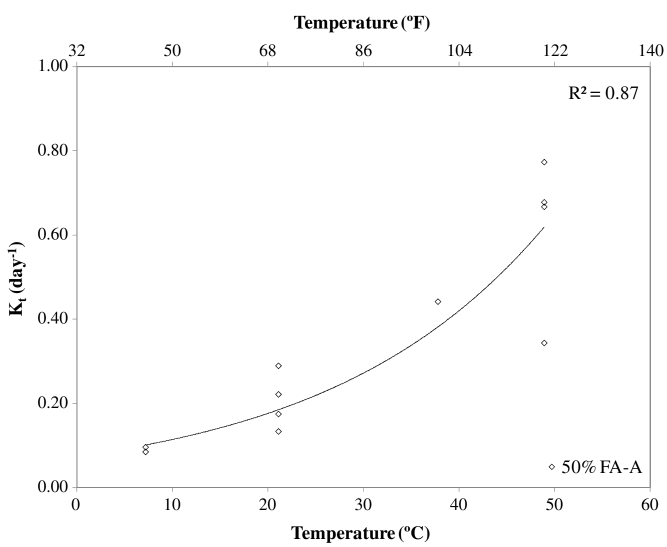

Fig. 1. Rate constant versus temperature for the 50% FA mixture

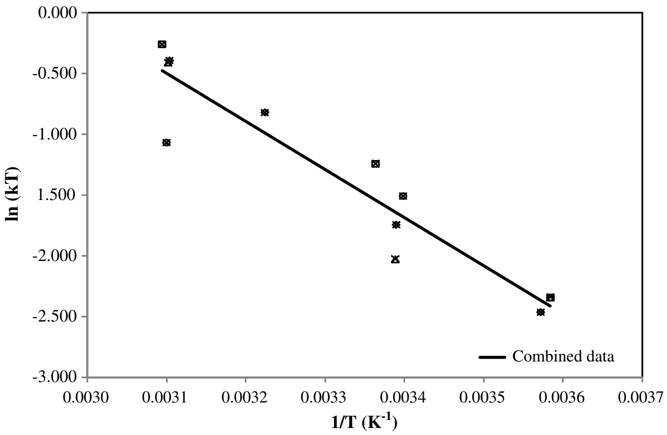

Fig. 2. Natural logarithms of rate constant values versus inverse absolute temperature for the 50% FA mixture

(A) mixture. To calculate the AE values, the natural logarithms of rate constant values were plotted as functions of the reciprocal of absolute temperature (curing temperature in Kelvin). An example of this plot is shown in Fig. 2 for the 50% FA mixture. The best-fit straight line was determined. The AE was calculated as the negative value of the slope divided by the universal gas constant. Table 5 presents the computed apparent AE values for the various mixtures. The addition of different amounts of FA alters the hydration process of concrete mixtures. As listed in Table 4, the increased FA content from 20 to 35%, maintaining the w/cm constant at 0.5, slowed down the hydration reaction, producing a much slower activation energy value. However, adjustments in the w/cm also affect the hydration behavior of concrete mixtures (Obla et al. 2008). As listed in Table 3, during mixture proportioning, an increase in FA content at higher cement replacement values (such as 50%) eventually requires an adjustment in the w/cm to achieve realistic rates and levels of compressive strength gain. Such combined effects of FA content (35 and 50%) and w/cm (0.50 and 0.39, respectively) for these mixtures produced different hydration kinetics. A consequence of the significantly higher value of w/cm in the 35% HVFA mixture was a retardation of the hydration reaction, which produced a lower activation energy than the 50% HVFA mixture. Such effects on the hydration kinetics were also reflected in the strength values, as listed in Table 6 The 50% HVFA mixture featured a significantly higher strength than the 35% HVFA mixture. The same effects on strength were observed from the field testing results reported in Table 8.

Strength/Maturity Model

Standard Cured Strength Results and Strength/Maturity Relationship

Compressive strength testing of standard-cured 100 × 200 mm (4 × 8 in.) concrete cylinders was performed to develop the strength/maturity relationship for the two mixtures with higher FA contents (35 and 50% FA). Table 6 summarizes the compressive strength results for the standard-cured cylinders of these mixtures. The equivalent age maturity function was used to compute the maturity index by using the calculated activation energies. The resulting strength versus equivalent age relationships were plotted by using the best fitting hyperbolic function. The hyperbolic function accurately characterized the strength/maturity relationship for all mixtures. An example is shown in Fig. 3 for the 50% FA mixture. These strength/maturity plots were later used to estimate the in-place compressive strengths of the concrete blocks and slabs that were constructed with the same mixtures under field conditions.

Table 5. Calculated Activation Energies per ASTM C1074

Mixture	AE (J/mol)
20% FA	48,100
35% FA	15,600
50% FA	33,400

Note: ASTM (2004). AE was calculated based on a combined data set from four trials.

Table 6. Compressive Strength Values

	35% FA		50% FA	
Age (days)	Equivalent age at 23°C (73°F) (days)	Strength [MPa (psi)]	Equivalent age at 23°C (73°F) (days)	Strength [MPa (psi)]
1	0.95	4.8 (699)	0.98	7.2 (1,039)
2	1.90	7.1 (1,034)	1.94	11.5 (1,662)
4	3.78	9.7 (1,402)	3.80	16.4 (2,372)
7	6.62	12.6 (1,820)	6.59	19.5 (2,832)
14	13.05	18.0 (2,609)	12.79	25.3 (3,668)
28	26.54	24.2 (3,505)	25.33	33.2 (4,811)

Field Testing Results

The concrete blocks and slabs were casted under ambient exposure conditions. Table 7 lists the average ambient temperatures during the first 96 h after placing the concrete in the block.

Figs. 4 and 5 show the in-place temperature histories of concrete blocks based on different curing conditions. The tem-

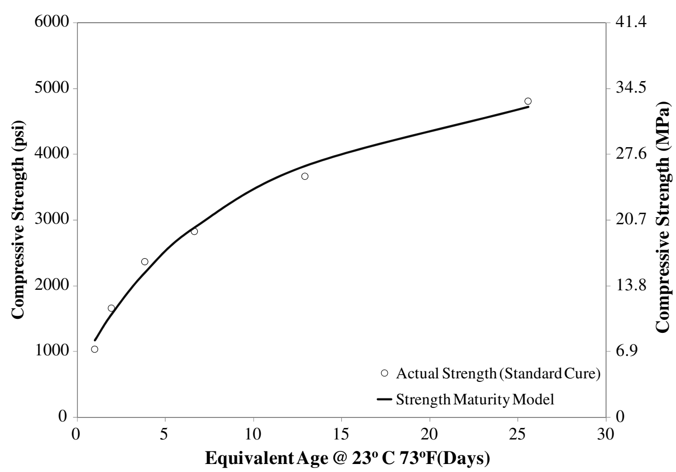

Fig. 3. Maturity model for the 50% FA mixture

Table 7. Placement of Concrete for Blocks and Slabs over the First 96 h

Mixtures	Block	Slab	Average ambient temperature [°C (°F)]
35% FA	X	—	10.0 (50.0)
50% FA	X	X	12.7 (55.0)

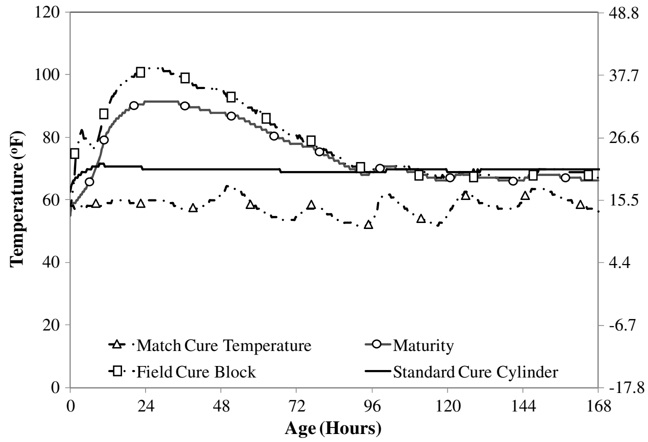

Fig. 4. Temperature profiles for the 35% FA mixture

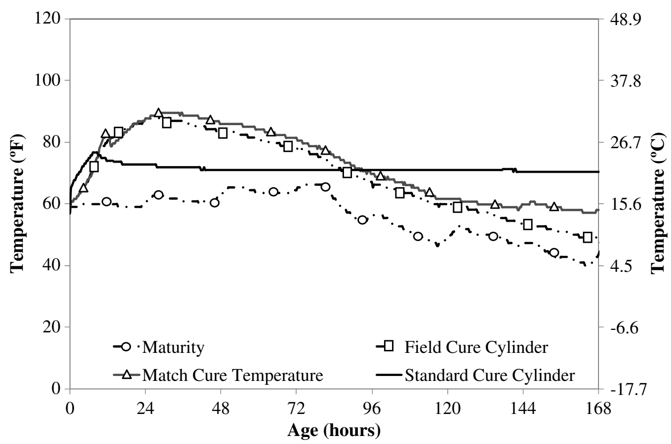

Fig. 5. Temperature profiles for the 50% FA mixture

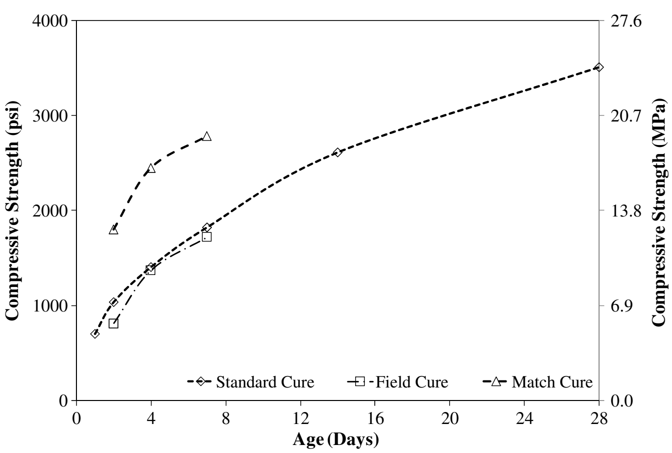

Fig. 6. Compressive strength versus age (35% FA mixture: block)

perature histories were recorded by using iButton temperature data loggers located 2.54 cm (1 in.) from the block surface and 5.08 (2 in.) from the slab surface. As shown by the temperature profiles, the match cure cylinders that replicate the actual temperature profile of the structural element (block and slab) experience higher temperatures than the field-cured and standard-cured cylinders.

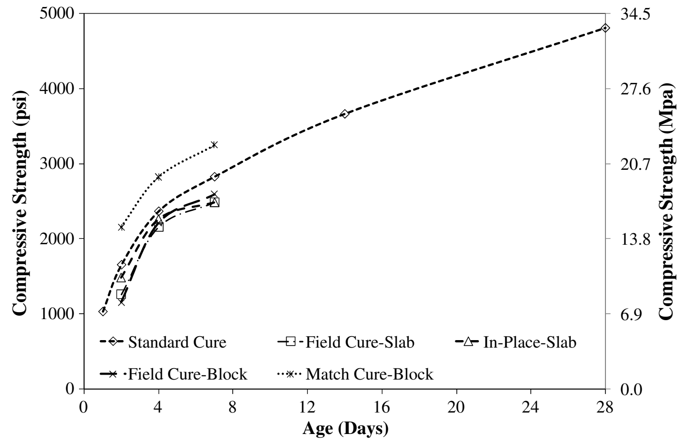

Fig. 7. Compressive strength versus age (50% FA mixture: slab and block)

It is well known that concrete cured at higher temperatures will more rapidly gain early-age strength than when it is cured at lower temperatures. Higher temperatures result in a faster rate of chemical reaction and thus a faster strength gain.

Figs. 6 and 7 illustrate the compressive strength plots for the various curing conditions of the two mixtures, including the data from the block and slab concrete elements. From the data collected from the comparative experiments, it was concluded that compressive strength measured using field or standard-cured cylinders does not accurately represent the conditions of the blocks or slabs and underestimate the in-place compressive strengths of the structural concrete elements.

Discussion

The maturity method was used to estimate the in-place strengths of the concrete in the field block specimens and slabs. These values were compared with the strength of match-cured cylinders, which is expected to represent the most accurate estimates of actual in-place strength. The strengths of the field-cured cylinders were also included in this comparison. The in-place temperature histories shown in Figs. 4 and 5 were used to convert the actual curing ages to equivalent ages using Eq. (1) and the computed activation energies for each specific mixture. After the equivalent age was calculated, the predetermined strength/maturity relationships (like the one shown in Fig. 3 for the 50% FA) were used to estimate the in-place strength at the locations of the iButton sensors at test ages of two, four, and seven days. Table 8 shows the actual ages and the estimated in-place strengths based on the maturity method, the strengths of the match-cured and field-cured cylinders, and the estimated strengths from pullout tests (i.e., pullout inserts included in each block for estimating in place strength using the correlation between pullout force and strength). The average percent difference between the match-cured cylinders and in-place strength estimations by field-cured cylinders, pullout tests, and maturity method are listed in Table 9. Figs. 8 and 9 show examples of strength comparisons for the block with the 35% FA mixture and the slab with the 50% FA mixture.

In general, the estimated strengths based on the maturity method were lower than those of the match-cured cylinders. This difference was even higher for the strength values of the field-cured cylinders, which can be explained by the lower in-place temperatures they experience, compared with the temperatures recorded by the

Table 8. Strength Comparison between Various Curing Conditions and Predicted Strength

Mixture	Concrete element	Actual age (days)	Match cure strength [MPa (psi)]	Strength prediction from maturity method [MPa (psi)]	Strength prediction from pullout correlation [MPa (psi)]	Field cure [MPa (psi)]
35% FA	Block	2	12.4 (1,802)	7.3 (1,058)	9.1 (1,325)	5.6 (813)
		4	16.9 (2,450)	10.2 (1,477)	9.5 (1,379)	9.5 (1,374)
		7	19.2 (2,786)	13.3 (1,925)	12.4 (1,804)	11.9 (1,722)
50% FA	Block	2	14.9 (2,156)	12.2 (1,769)	14.8 (2,151)	8.0 (1,155)
		4	19.5 (2,823)	16.8 (2,434)	15.9 (2,311)	15.3 (2,216)
		7	22.4 (3,251)	19.9 (2,887)	16.8 (2,441)	17.9 (2,599)
	Slab	2	10.3 (1,491)	10.0 (1,448)	9.3 (1,349)	8.7 (1,263)
		4	15.6 (2,262)	13.9 (2,014)	12.7 (1,844)	14.9 (2,159)
		7	17.6 (2,545)	17.6 (2,550)	15.4 (2,240)	17.1 (2,485)

Table 9. Average Differences between Match-Cured and Other In-Place Strength Predictions

Mixture	Concrete element	Strength prediction maturity method change (%)	Strength prediction from pullout correlation change (%)	Field cure change (%)
35% FA	Block	37.3	35.1	45.7
50% FA	Block	14.3	14.4	29.3
	Slab	4.6	13.3	7.4

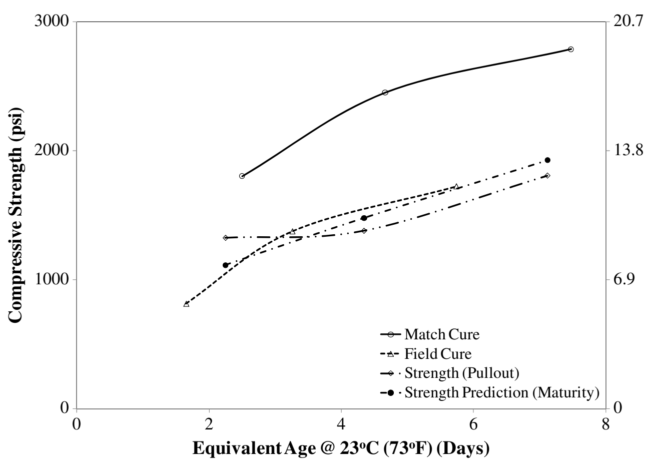

Fig. 8. Strength versus equivalent age (35% FA block)

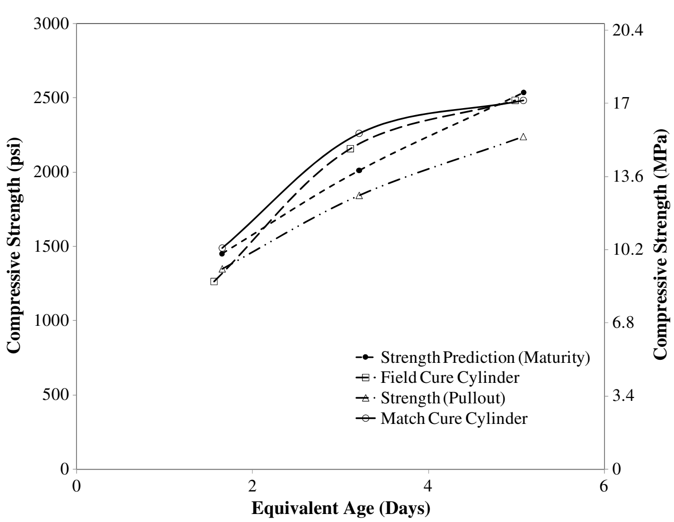

Fig. 9. Strength versus equivalent age (50% FA slab)

iButton sensors within the block. Estimated strengths from pullout tests and maturity generally agreed well. Additionally, although the data from the thermocouple used to drive the match-cured cylinders and the iButton data loggers used to calculate equivalent age for the maturity method were similar, the thermocouple temperatures were consistently higher. Therefore, at each test age, the match-cured cylinders were at a higher equivalent age than was used to estimate strength from the strength/maturity relationship. This may account for some of the consistently lower estimated strengths based on maturity. Other specific reasons for the differences in such values are discussed next, based on the results for each mixture.

Regarding the 35% FA mixture, at the test age of seven days, the equivalent age of the block was 7.1 days. The seven-day strength of the standard cured cylinder was 12.6 MPa (1,820 psi). The estimated strength for the maturity method (13.3 MPa; 1,925 psi) is consistent with this value, but the match cured strength is significantly higher at 19.2 MPa (2,786 psi), as listed in Table 8. This result is related to the maximum in-place temperature in the block (Fig. 4), which was approximately 33.3°C (91°F). The mortar tests indicated that when mortar cubes were cured at 37.8°C (100°F), the estimated long-term strength was greater than for room-temperature curing. This apparent strength enhancement attributable to higher early age temperature in the fly ash mixtures may explain why the match-cured cylinders were stronger than estimated from the strength maturity relationship. However, the pullout test was lower at seven days, equal to 12.4 MPa (1,800 psi), possibly owing to thermal strains introduced in the surface layer after formwork was removed at three days.

For the 50% FA mixture, at test ages of two, four, and seven days, the computed equivalent ages of the block specimens were 2.4, 4.6, and 6.6 days, whereas for the slab, the corresponding values were 1.6, 3.2, and 5.1 days. Thus, the slab temperatures were lower than the standard temperature. For the concrete block, the match-cured cylinder strengths were considerably greater than the estimated strengths based on the maturity method. This is attributed to the strength-enhancing effect of the higher early age temperature in the block (Fig. 5), which reached 33.3°C (91°F). At the seven-day test age, the match-cured cylinder strength was 22.4 MPa (3,251 psi), as listed in Table 8. On the other hand, the seven-day standard-cured strength was 19.5 MPa (2,832 psi). For the slab, because the in-place temperatures were not higher than the standard temperature, this temperature related strength enhancement was absent. As a result, there was reasonable agreement between the match cured cylinder strengths and the estimated strength based on maturity (Table 8). The estimated strengths based on the pullout test agreed well with the strengths of the match-cured cylinders at the two-day test age. At four and seven days, the estimated strengths from pullout were considerably lower than the match-cured cylinders, reflecting the previously mentioned potential thermal strains that reduce the pullout resistance in the surface layer.

Additionally, it was mentioned that the mortar cubes of HVFA mixtures have shown increased long-term strengths when cured at higher temperatures than cubes cured at lower temperatures. Thus, such effects need to be further examined to improve strength estimation using the maturity approach. Thus, the AE of HVFA mixtures can be further validated with alternative approaches to ASTM C1074 (2004), such as that proposed by Obla et al. (2012a), in which the measured 28-day strength at the control curing temperature (73°F) is considered to be the ultimate strength (Su), and the analyses are based only on the test results up to 70% of this Su value, because maturity is used for early strength predictions in which approximately 70% of the 28-day strength is achieved. The revised AE values from this alternative approach may eventually produce predicted strength values that are closer to that observed with the match cure cylinders.

Conclusions

Overall, this study indicated that compressive strength measured from field-cured and standard-cured cylinders does not provide reliable estimates of in-place strengths for concrete structures. The match cured strength test data clearly demonstrated that HVFA concrete in actual structures has much higher early age strengths than those measured by testing cylinders that were cured under standard laboratory conditions. This effect reflects the amount of heat retained in a concrete member in the field as a function of its mass concrete characteristics, such as the dimensions of the concrete blocks and typical pavement concrete slab thicknesses of 0.34 m that were used in this study. On the other hand, thinner concrete structural members may not retain as much heat, and thus, the concrete mixture experiences lower temperatures during the hydration process. The fact that concrete mixtures on actual structures may experience much higher early age strengths than the laboratory and field cylinders implies that mixture proportions may be further optimized (with the use of lower total cementitious contents, increased quantity of FA, and/or higher w/cm) without negative effects to construction operations. The estimated strength based on maturity and pullout testing was 15 to 20% lower than match-cured cylinder strengths at identical actual early ages of two to seven days. However, they were far more accurate than field cured cylinders, which were approximately 20 to 50% lower. Finally, the mortar cube results indicating that higher curing temperatures produce higher long-term strengths highlight the need to further validate the AE of HVFA mixtures with alternative methods. The analysis method and results of this study can additionally be transferred to where similar materials are used and the findings can be further expanded with additional types and contents of FA.

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