ABSTRACT

Title of Document: ENHANCED MATURITY MODELING ANALYSIS FOR SUSTAINABLE CONCRETE MIXTURES USING HIGH VOLUME FLY ASH.

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Construction industry is reluctant to use high volumes of fly ash in concrete due to slower rate of strength gain observed in high volume fly ash concretes. Fly ash, a by-product of coal industry, is readily available on large scale, has cementitious properties and can be used as cheaper substitute for cement. In case of large concrete structures, a phenomenon known as mass effect is observed which cures the concrete at higher temperature thereby accelerating the rate of strength development in early ages. The aim of this research is to demonstrate that, although the rate of strength gain is slower in HVFA concrete, sufficient early age strength is developed due to mass effect observed in large concrete structures. A 14-day maturity based approach was adopted to develop prediction models

which can estimate in-place strength of HVFA concrete mixtures by taking into account the mass effect of concrete. The results maturity are compared against the existing methods and also with 28-day based maturity models and attempt is made to select the best approach of in-place strength determination.

ENHANCED MATURITY MODELING FOR SUSTAINABLE CONCRETE MIXTURES USING HIGH VOLUME FLY ASH.

By

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Thesis submitted to the Faculty of the Graduate School of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of
Master of Science
2015

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Preface

A major decision in construction industry today revolves around predicting the in-place strength of concrete and the timely removal of formwork. The removal of formwork can be facilitated when the concrete develops sufficient strength for the purpose for which it is cast. Due to its slower rate of strength gain, the construction industry is reluctant to use high volume fly ash (HVFA) concrete. Past research indicates that the slower rate of strength gain can be offset by the high in-place hydration that takes place inside large concrete structures. The aim of this research is to develop 14-day based maturity models to capture this high in place hydration and develop prediction models to estimate in-place strength of concrete mixtures. Four types of mixtures were analyzed in this research: one conventional concrete mixture, concrete mixture with 35% of type F fly ash, concrete mixture with 50% of type F fly ash and concrete mixture with 35% of type C fly ash. Three different approaches to calculate activation energy were considered and prediction models based on each approach were developed. Each approach was based on 14-day data. The first approach was based on ASTM C1074, also known as variable S_u approach. In this approach, the limiting strength of each mixture was considered different at different curing temperatures. The second was based on setting time of each mixture and is known as setting time approach. The third approach was known as constant S_{uc} approach. In this approach, the limiting strength for each mixture was kept constant irrespective of curing temperature. The results of in place strength estimated from the 14-day maturity based prediction models of each mixture were compared with the results from the existing methods of in place strength determination like field cured method, pullout testing, match curing and the 28-day based maturity models available from previous phase of research. In pullout testing, a metal insert is embedded in concrete at specific locations and the force required to pull it out is determined. This force is correlated with the compressive strength of concrete. In match curing, the actual temperature profile of concrete structure is replicated in testing cylinders through the use of temperature sensors and micro-controllers. The pullout force and compressive strength correlations developed in this research were based on 14-day data. Based on this research, the following primary conclusions were reached: the 14-day maturity models show improvement in estimating the in-place compressive strength for fly ash of type F over the 28 –day maturity model; the 14-day setting time approach that was explored in this research has shown encouraging results and this approach can be used for developing prediction models; the 14-day setting time method and 14-day maturity method consistently provide lower errors of prediction errors than the 28-day maturity models for all the HVFA concrete mixtures.

Dedication

To my late grandparents, **Mr. Vasudeo Pendharkar** and **Mrs. Sudha Pendharkar**

Acknowledgements

I would sincerely like to thank my research advisor, Dr. Dimitrios Goulias, under whose constant guidance and support, this research was possible. The opportunity of working with Dr. Goulias over the course of this research has truly enriched me technically, personally and professionally. For that, I am deeply indebted to him.

I would also like to express my gratitude to Dr. Aggour and Dr. Amde for agreeing to be a part of my defense committee. Their quick and timely responses to my concerns helped smoothen the process of thesis defense.

I thank my parents and brother for their unwavering support and unconditional love. Their continued faith has always inspired and motivated me. Lastly, I want to thank all my friends and other family members who have stood by me during thick and thin.

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Chapter 1 Introduction

1.1 Research Outline

An important decision in the construction industry today revolves around the in-place strength gain predictions and the timely removal of formwork. Traditionally, ASTM C39 is used to estimate the strength of concrete at the required age. Concrete samples are subjected to same curing conditions as expected on site and samples are tested at specific ages to determine compressive strength. The method is simple to execute and very reliable. However, in implementation of ASTM C39, 'mass effect' of concrete is often overlooked which may provide higher in place strengths at early ages. In the case of mass concrete structures, a large amount of heat is generated due to exothermic reaction between the cement and water. As a result, internal temperature of concrete is significantly higher and concrete cures faster and thus develops strength earlier.

The objective of this research was to develop strength prediction models which can estimate strength at early ages by minimizing concrete testing. These approach should eventually capture the mass concrete effects more accurately than the standard curing described in ASTM C39.

Another objective of the research was to study the strength development in High Volume Fly Ash (HVFA) concrete mixtures. Fly Ash is a byproduct of coal used by the electric industry and is known to have cementitious properties. About 131 million tons of fly ash is produced annually in the United States and disposal of fly ash poses an environmental challenge. Because of its large scale availability, low cost and cementitious properties, and potential improvement in concrete properties, Fly Ash became popular in the construction industry as a replacement for cement. Small replacement of cement by fly ash (about 5%-10%) doesn't impact the hydration reaction significantly but large scale replacement (about 20%-50%) is known to slow down the hydration reaction and hence strength develops slowly. The construction industry is averse to using HVFA concrete due to this reason. However, the slow development is also partly due to fact that often the mass effect is neglected.

1.2 Research Methodology

The aim was to develop strength prediction models for conventional and HVFA mixes. The HVFA concrete mixes were developed based on the conventional (control) mixture and using varying amounts of two types of fly ash: Type F and Type C (these are explained further in Chapter 3). In all, 4 mixes were studied (one conventional mix and three HVFA mix) and their corresponding prediction models were developed by using alternative methods capturing the hydration effects. The need for considering two types of fly ash is to compare the effects of chemical composition of fly ash on the rate of strength development.

This research is further extension of Dr. Sushant Upadhyaya's research titled "Early Age Strength Prediction for High Volume Fly Ash Concrete using Maturity Modeling." Dr. Upadhyaya's work was based developing prediction models using maturity modeling based on 28-day strength data. The rate of strength development in concrete slows down considerably from the 14th to the 28th day. Thus, a prediction model based on the 14-day data is may provide accurate strength prediction values and eventually require less testing. Thus, the focus of this research was to develop 14-day based prediction models and then compare the results with those obtained from alternative methods and the the 28-day Maturity approach suggested by ASTM 1074. The research also included two alternative methods of developing 14-day based prediction models, one based on the setting time of concrete and a second one considering the constant S_{uc} approach (i.e., all mixtures have the same ultimate strength). Chapter 4 describes in detail the alternative modeling approaches adopted in this research in order to develop the strength prediction models. The major tasks in this research were as follows:

1.2.1 Activation Energy

The first step in developing prediction models for different mixes is to determine the activation energy of the corresponding mixes. ASTM C1074 gives the procedure for determining the activation energy by the maturity method. As per Arrhenius, Activation energy is defined as the minimum amount of energy required to start a chemical reaction between potential reactants. In the context of this research, activation energy is the energy required to start the hydration reaction. The activation energy was calculated using three different approaches: Variable S_u Approach, Setting Time Approach and Constant S_{uc} Approach. These three approaches correspond to the three different ways in which the predictive maturity models were developed. The procedure for finding the activation energy using these approaches is included in detail in Chapter 4.

1.2.2 Maturity Modeling

As mentioned earlier, models were developed for four type of concrete mixes. Concrete testing was carried out at the previous research phase (Upadhyaya, 2008) where concrete cylinders were subjected to standard curing in the laboratory as per ASTM C39. Cylinders were made corresponding to each of the four mixes. The cylinders were then tested at the ages of 1,2,4,7, 14 & 28 day to determine the corresponding compressive strength as per ASTM C39. At each testing age, an average of three test cylinders was reported as compressive strength for that age. Temperature sensors were placed in two of the concrete cylinders to monitor temperature profile during curing. The raw data for strength at respective ages for all the mix was available through Dr. Upadhyaya’s earlier work. Using the activation energy, the actual age at 1,2,4,7 & 14 day were converted to equivalent age @ 23^0 C. Chapter 2 explains in detail such procedure.

1.2.3 Match Curing

As mentioned earlier, large concrete structures (mass concrete effects) may experience higher internal temperatures due to the exothermic reaction between the cement and water. Inability to take this into account will lead to under-prediction of strength. To account for such effects the match curing approach was adopted. In match curing, the cylinders to be tested for strength are subjected to the same temperature profile as the large concrete structure on site. This is achieved by inserting temperature sensors inside the concrete, on site, and at specific locations within the mass structure. The temperature profile of concrete can then be monitored and used to cure the concrete cylinders. The higher temperature causes faster curing and concrete gains strength at a faster rate. The strength achieved from match curing is eventually representing most accurately the on-site concrete strength. Thus, the accuracy of the strength prediction models can be judged on how well the predicted values compare with those from the match cured strength values. Due to testing logistics the match curing method adopted in the previous phase of this research was limited to 2, 4 and 7 days (Upadhyaya, 2008). Thus since match curing strength was not available at 28 days, a part of this research was dedicated to predict the match cured strength at 28 days. Based on the experimental data and past attempts suggested in the literature (discussed in Chapter 2), a basic structure for the model development process was identified and the best-fit equation was used. This allowed to predict the 28-day strength. The procedure, analysis and discussion regarding match curing is further addressed in Chapter 4.

1.2.4 Field Curing

Field curing testing was also included in the previous phase of the research and the data were used for the analysis of this work. The field cured cylinders were tested for strength at 2, 4 & 7 days. For each age, the average of 3 cylinders was recorded as compressive strength. The field curing strength data are discussed in in Chapter 4.

1.2.5 Pullout Tests

ASTM C900 describes the procedure for determining the pullout strength of concrete. A metal is inserted in concrete and this test determines the force (known as pullout force) required to remove the metal insert from the concrete structure. This is a non-destructive test. The idea is to determine the pullout force and use the pullout force vs compressive strength to relate the two. Usually, the manufacturers of pullout testing apparatus provide the correlations between pullout strength and compressive strength. As per ACI 228.1R-03, this correlation is of the following form: $C = a \times P^b$

Where: C = Compressive strength MPa (psi),

P = Pullout force (kN)

a , b = Regression constants (MPa, psi)

The pullout test data was available from the past research phase and to have better strength predictions, the correlation between pullout force and compressive strength were developed for these specific concrete mixtures. This analysis is discussed in Chapter 4.

1.3 Organization of Thesis

Chapter 2 provides the background for maturity modeling and its development. The methods for calculating the activation energy are discussed in that chapter as well.

Chapter 3 provides information on raw materials used in this research. The chemical composition of different types of fly ash, mix design proportion for the conventional and HVFA concrete mixtures along with the source of raw materials are summarized in detail in this chapter.

Chapter 4 includes the modeling analysis and results. It describes the different approaches that were adopted to develop the prediction models. The procedure for calculating activation energy, maturity modeling, match curing, field curing and pullout testing are explained in detail along with the results.

Chapter 5. This chapter describes the results from alternative methods of maturity modeling. The predicted values of strength from the prediction models developed in this research are compared with the models developed in the previous phase of the study (Upadhyaya, 2008) to determine the best approach for each mixture.

Chapter 6 provides the conclusions. The findings of the modeling and their accuracy is summarized in this chapter.

Chapter 2 Background

2.1 Development of Maturity Functions

Concrete gains strength over a period of time. The rate of strength gain of concrete can be accelerated, among other, by curing the concrete at higher temperature. The rate of strength gain can be accelerated by curing at higher temperature, but such effects are not expected on the ultimate strength. Thus, the rate of strength gain in concrete can be controlled by increasing curing temperature and increasing curing time (or age), among other means like proportioning and use of chemical admixtures. The effects of temperature and time on concrete can be explained by the term 'Maturity Function'.

As explained in ASTM C1074, maturity function is a mathematical expression which summarizes the time-temperature history of concrete (or cementitious mixture) during the curing period to calculate an index known as maturity index. The main objective of this function is to explain the combined effects of time and temperature on strength development at elevated curing temperatures.

The Nurse-Saul equation is a popular maturity equation named after the works of Nurse (1949) and Saul (1951) and is defined in ASTM C1074.

The Nurse-Saul Equation is given by

$$\boldsymbol{M = \sum(T_a - T_o)\Delta t} \qquad \textbf{Equation 1}$$

Where, M = Nurse-Saul maturity index at age t (°C • hours),

T_a = average concrete temperature during the Δt (°C),

T_o = datum temperature (°C), and

Δt = time interval (hours).

Thus, according to Nurse-Saul equation, the product of temperature and time is good representation of maturity of concrete. It is important to note that the process of strength development starts above a temperature known as datum temperature. The minimum temperature above which concrete begins to develop strength is known as Datum Temperature.

The basic idea is that concrete of same mix with same maturity index (product of temperature and time) will have same strength irrespective of the curing history. For example, concrete cured at 25

°C for 10 days will have same strength as concrete cured at 50 °C for 5 days, if they are of the same mix. This is because both have the same maturity index of 250 °C • Day. The Nurse-Saul equation represents one of earliest works in developing maturity functions.

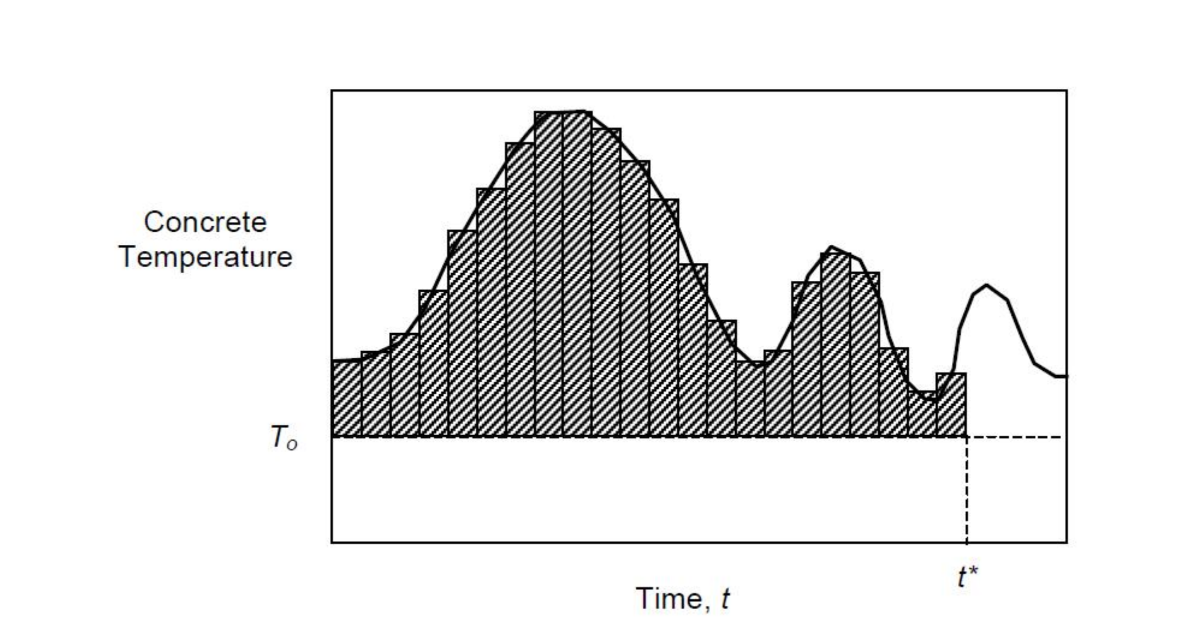

Figure 2.1: Temperature vs Time history of Concrete calculated according to Equation 1 (Carino 1984)

According to Nurse-Saul equation, the rate of strength gain is a linear function of time. However, this is not true. When cement (or cementitious material) and water are mixed, there is time delay before the process of strength development begins. In other words, the process of strength development is not instantaneous. This time delay period is called Induction period (Carino and Lew, 2011). After the induction period is the acceleratory period: the period where strength develops rapidly (Carino and Lew, 2011). The strength develops rapidly for initial days and beyond about 28-days, the rate of strength development becomes slower and slower. Due to this, a linear approximation is not a very accurate measure of maturity and there was a need to come up with alternatives for the widely accepted and popular Nurse-Saul equation.

The age of concrete is relative to the curing temperature. At higher temperatures, concrete cures faster. The standard curing temperature as defined in ASTM C39 is 23°C. Thus, if the curing is carried out at any temperature other than 23°C, the practice is to represent age of concrete in terms of equivalent age @ 23°C.

The equivalent age @ 23°C is defined as the age of concrete @ 23°C for which the concrete would have had the same maturity had it been cured at 23°C. The equivalent age of concrete is mixture specific i.e. the equivalent age will be different for different mixes. If the rate of hydration reaction is faster, the concrete matures quickly and hence, the equivalent age @ 23°C will be low. Conversely, if the rate of reaction is slower, it takes time for concrete to mature and gain strength and therefore, the equivalent age @ 23°C will be higher. The rate at which the reaction proceeds, therefore, becomes an important factor in maturity modeling. The rate of reaction is decided by the ‘Activation Energy’ of the mix.

Activation Energy is defined as the minimum energy required for reaction to start and proceed. Arrhenius developed an equation, now known as the Arrhenius Equation, which captured the temperature dependence of reaction rates through the concepts of activation energy. Freiesleben, Hansen and Pedersen (1977) developed a new maturity function based on the ideas of Arrhenius equation.

This equivalent age equation is as follows:

$$\mathbf{t_e = \sum_0^t e^{\frac{-E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} . \Delta t} \qquad \textbf{Equation 2}$$

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 curing period, Δt

T_r = absolute reference temperature, Kelvin

In this research, the above maturity function is used to compute the equivalent ages.

2.2 Strength-Equivalent Age Relationship

The aim of this research is to develop models which can predict the strength of concrete at required age with fair accuracy. To be able to do this, it is essential to know the variation of strength over a period of time. It is already well known that concrete begins to develop strength after the induction period and develops strength rapidly during the early ages and rate of strength development slows down with time. However, concrete continues to gain strength throughout the course of its life. The challenge now is to capture this behavior through a mathematical model.

Carino (1984) developed a hyperbolic equation which could capture this behavior provided the curing was carried out under isothermal conditions up to equivalent ages of 28-days at standard curing temperature of 23 °C.

This equation is as follows:

$$S_t = S_u \frac{k(t-t_0)}{1+k(t-t_0)}$$ **Equation 3**

Where, S_t = strength at age

S_u = limiting strength,

k = rate constant, 1/day, and

t_0 = age at start of strength development.

In the above hyperbolic equation, the strength is assumed to develop after the final setting time of the mixture. The values of setting time for all the mixtures are given in table 4.1.

Equation 3 is used in this research for developing maturity models to predict strength of concrete at required ages.

The term S_t represents the strength of concrete at age‘t’ days. Following the guidelines given in ASTM C39, the strength of concrete can be found out at the required age. Thus, we can find out the term S_t and the corresponding age of the mix as well. Once this data is obtained, the best fit curve is applied to the data and the from the equation of this best fir curve, the rate constant ‘k’ and limiting strength ‘S_u’ can be found out.

In this research, Matlab was used to develop the strength – equivalent age @ 23°C relationship using equation 3.

Chapter 3 Materials & Concrete Mix Design

This research follows the initial work carried out in a previous experimentation (Upadhyaya 2008) titled 'Early Age Strength Prediction for HVFA Concrete Using Maturity Modeling'.

3.1 Raw Materials

A no.57 crushed limestone coarse aggregate and natural sand conforming to ASTM C33 was used to prepare the concrete mixtures and samples for testing. Table 3.1 lists the gradation properties for the aggregates used. The gradation for the coarse and fine aggregates was carried out as per the provisions of ASTM C136. The ASTM C136 provides the procedure for sieve analysis of coarse and fine aggregates.

Table 3.1: Gradation of Coarse and Fine Aggregates

Percent Passing		
Sieve Sizes	Coarse Aggregate	Fine Aggregate
	No 57	-
1 ½	100	0
1	100	0
¾	92	0
½	49	0
3/8	28	100
No 4	5	99
No 8	1	84
No 16	0	70
No 30	0	52
No 50	0	20
No 100	0	3
No 200	1	-

Apart from gradation analysis, the aggregates were also tested for some specific properties like absorption, specific gravity etc. Table 3.2 provides the properties of coarse and fine aggregates used in this research.

Table 3.2: Properties of Coarse and Fine Aggregates

Properties	Coarse Aggregate	Fine Aggregate
Fineness Modulus	-	2.73
Specific Gravity (SSD)	2.84	2.59
Absorption,%	0.30	1.30
Dry rodded unit weight, lb/ft^3	105.90	N/A

Type I Portland Cement conforming to ASTM C150 was used for preparing the concrete mixes. Two types of fly ash were used conforming to specification of ASTM C618:

1. Class F fly ash having CaO content of 1.0 %. This fly ash wasidentified as FA-A henceforth throughout the course of this research.

2. Class C fly ash having CaO content of 23.44 %. This fly ash was identified as FA-C henceforth throughout the course of this research.

Apart from this, Polycarboxylate based Type F High Range Water Reducer (HRWR) conforming to specifications of ASTM C494/C494M was used.

The fly ash and the HRWR admixtures were procured from the following sources:

i) FA-A was procured from STI, Baltimore, MD,

ii) FA-C was procured from Boral Material Technologies Inc.,

iii) HRWR admixture was supplied by Sika Corporation.

3.2 Mixture Proportion

For ease of testing and convenience, testing the actual concrete specimen is not preferred. Whenever possible, corresponding mortar mixes are prepared such that they preserve the integrity of the actual concrete mix. This can be achieved by proportioning the mortar mixes such that the fine aggregate-to-cementitious materials ratio (by mass) is the same as coarse aggregates-to-cementitious materials ratio. This is consistent with the recommendations of ASTM C1074 Annex A1. A major task in this research involved determining the activation energy. The activation energy was determined using the mortar mixes by proportioning them as described above. The actual mix design proportions are tabulated below.

Table 3.3: Mix Design Specifications for Mortar Mixes

Item	Control Mix	35 % FA-A Mix	50 % FA-A Mix	35 % FA-C Mix
Cement (grams)	1876.00	1199.00	1101.00	1357.00
Fly Ash (grams)	0.00	710.00	1066.00	740.00
Fine Aggregate (grams)	7136.00	7087.00	7036.00	7250.00
Water (grams)	1052.00	960.00	848.00	889.00
HRWR Admixture (ml)	62.90	200.67	212.64	152.75
w/cm	0.56	0.51	0.39	0.42

The next part of research focused on developing the prediction models for different concrete mixtures. The process of developing these models is explained in detail in Chapter 4. As a part of this process, standard concrete cylinders 10.2cm X 20.3cm (4in by 8in) were required to be made for all the mixtures given in table 3.3 for purpose of compression testing as per ASTM C39. The mix design proportions for making these cylinders is given in table 3.4.

Table 3.4: Mix Design Proportions for Concrete Cylinders

Item	Control Mix	35 % FA-A Mix	50 % FA-A Mix	35 % FA-C Mix
Cement, kg/m^3	302.60	196.40	182.70	215.40
Fly Ash, kg/m^3	0.00	116.30	176.80	117.50
Coarse Aggregate, kg/m^3	1151.00	1160.40	1167.00	1151.00
Fine Aggregate, kg/m^3	770.10	752.30	769.50	783.70
Water, kg/m^3	169.70	157.20	140.60	141.20
HRWR Admixtures, ml/45kg	62.90	200.70	140.60	152.70
w/cm	0.56	0.50	0.39	0.42

Chapter 4 Experimental Work, Analysis and Results

The aim of this research is to develop maturity based prediction models which can predict the strength of concrete fairly accurately for required ages. To this effect, different approaches were tried. The determination of activation energy of the four different concrete mixes under consideration was one of the major tasks of this research.

4.1 Determination of Activation Energy

4.1.1 Activation Energy by ASTM C1074

ASTM C1074 describes the procedure for estimating the concrete strength by maturity method. The process of determining activation energy can be considered as a two-step process. Firstly, the rate constant for the reaction is determined and from the rate constant, the activation energy can be determined. Initially, mortar mixes representative of respective PCC and HVFA mixes are prepared. Annex A1 of ASTM C1074 clearly states that values of activation energy obtained by analyzing mortar mixes are applicable to corresponding concrete mixes. Once the cubes of mortar mixes are cast, compressive strength test is performed on them as per ASTM

C39 at various ages. Thus, for a specific mix, the aim is to achieve a set of values of strength of that mix at various ages under different curing conditions. Once this data is obtained, Equation 3 as described in chapter 2 is used to find the rate constant. This equation is as follows:

$$S_t = S_u \frac{k(t - t_0)}{1 + k(t - t_0)}$$

In the above equation, '*k*' represents the rate constant. The values of S_t were recorded for t = 1,2,4,7 and 14 days. This is because the primary aim of this research is to develop maturity models based on 14-day data and hence, even though available, the data beyond 14-days was included only for comparison The values of S_t are plotted against respective values of age t and best fit curve is applied to this set of data. This best fit curve then provides the value of rate constant.

ASTM C1074 recommends preparing mortar cubes of size 5.08 cm (2 in) for determination of activation energy. For different mixes, the mortar cubes were prepared based on mix design proportions given in table 3.3. The cubes were cured at four different curing temperatures of 7.5 ^{0}C (45 ^{0}F), 21^{0}C (70 ^{0}F), 38^{0}C (100 ^{0}F) and 49^{0}C (120 ^{0}F). There were 4 different mixes and mortar cubes representing each mix were prepared and cubes of each mix were cured at four different temperatures as given above. For each mix at each testing age, three 5.08 cm (2 in) mortar cubes were tested and average of the three was recorded as the compressive strength at that age.

The strength vs age data for the different mixes can be obtained from previous phase of research (Upadhyaya, 2008). As can be seen in Equation 3, the setting time for different mixes are required to determine the rate constant. The setting time test was performed on different mixes as per ASTM C403 to achieve this data. This data is tabulated below.

Table 4.1: Setting Time for Mortar Mixtures (ASTM C403)

Mixture	T_c=7.5 °C (45 °F)		T_c=21 °C (70 °F)		T_c=38 °C (100 °F)		T_c=49 °C (120 °F)	
	Initial (hrs)	Final (hrs)	Initial (hrs)	Final (hrs)	Initial (hrs)	Final (hrs)	Initial (hrs)	Final (hrs)
Control Mix	7.80	15.00	4.70	8.50	2.90	4.10	1.80	2.50
35% FA-A Mix	10.20	17.10	6.60	13.20	5.00	7.10	3.00	4.20
50% FA-A Mix	10.90	19.90	7.30	14.10	5.70	8.40	3.30	5.00
35% FA-C Mix	8.00	16.00	5.70	11.40	4.10	5.90	2.40	3.50

Table 4.1 provides the setting times for the different mortar mixes under various curing conditions. Using the data given in this table and strength data from previous phase of research, equation 3 as given above can be used to find the rate constant *k*.

In the previous work (Upadhyaya, 2008) the rate constants for the mixes were based on 28-day strength data while the values determined in this research were based on 14-day strength data. Table 4.2 provides the values of rate constant based on 14-day while also comparing the values based on 28-day strength data.

Table 4.2: 28-day vs 14-day k value comparison

Mixture	Trial	7.5°C (45 °F) k_t (day^{-1})		21°C (70 °F) k_t (day^{-1})		38°C (100 °F) k_t (day^{-1})		49 °C (120°F) k_t (day^{-1})	
		k_{T-28}	k_{T-14}	k_{T-28}	k_{T-14}	k_{T-28}	k_{T-14}	k_{T-28}	k_{T-14}
Control Mix	1	0.240	0.315	0.636	0.884	1.539	1.880	2.450	2.536
	2	0.203	0.246	0.648	0.809	-	-	1.973	2.134
35% FA-A Mix	1	0.156	0.173	0.410	0.737	0.457	0.961	0.404	1.316
	2	0.161	0.168	0.310	0.359	-	-	0.542	0.619
	3	-	-	0.290	0.373	-	-	0.309	0.441
50% FA-A Mix	1	0.085	0.085	0.175	0.235	0.441	0.738	0.677	0.827
	2	0.096	0.103	0.289	0.387	-	-	0.772	0.856
	3	-	-	0.133	0.476	-	-	0.666	0.592
35% FA-C Mix	1	0.056	0.049	0.198	0.254	0.138	0.170	0.335	0.330
	2	-	-	0.194	0.251	-	-	0.335	0.342
	3	-	-	0.013	0.120	-	-	0.039	0.184

Where $k_{T-28} = k_T$ value based on 28-day data
$k_{T-14} = k_T$ value based on 14-day data

The k_{T-28} values given in table above are from the previous study (Upadhyaya, 2008) while the k_{T-14} were computed as a part of this research. There was a wide variation in error when predictions were based on 28-day model and for this reason an approach based on 14-day model was suggested. From Table 4.2, it can be seen that every

14-day rate constant value is higher than the corresponding 28-day based rate constant value.

Once the values of rate constant have been determined, Annex A1 in ASTM C1074 provides further directions to compute activation energy. The natural logarithms of rate constant is calculated along with absolute temperature of curing (kelvin = Celsius + 273). A plot of natural logarithm of *k*-values is plotted against the reciprocal of absolute temperature. These plots are known as Arrhenius plots. A best fit line is then determined for these plots of data. The negative slope of this line is the activation energy divided by the universal gas constant R. Thus, activation energy can be determined by multiplying the negative slope of best fit line by Universal Gas constant R.

The Arrhenius plots for all the four mixes are shown below. Since multiple trials were prepared for each mix, the Activation Energy values were determined by taking the combined data from all trials into consideration and is denoted by ‘combined AE’ in table 4.3.

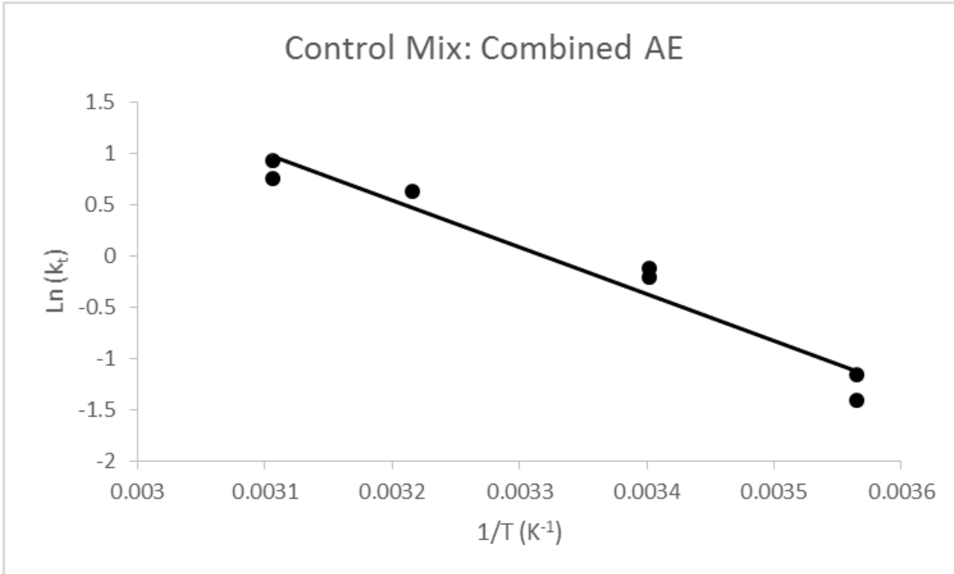

Figure 4.1: Arrhenius Plot for Control Mixture based on 14 days data
Activation Energy of Control Mix = 38067.55 J/Mol

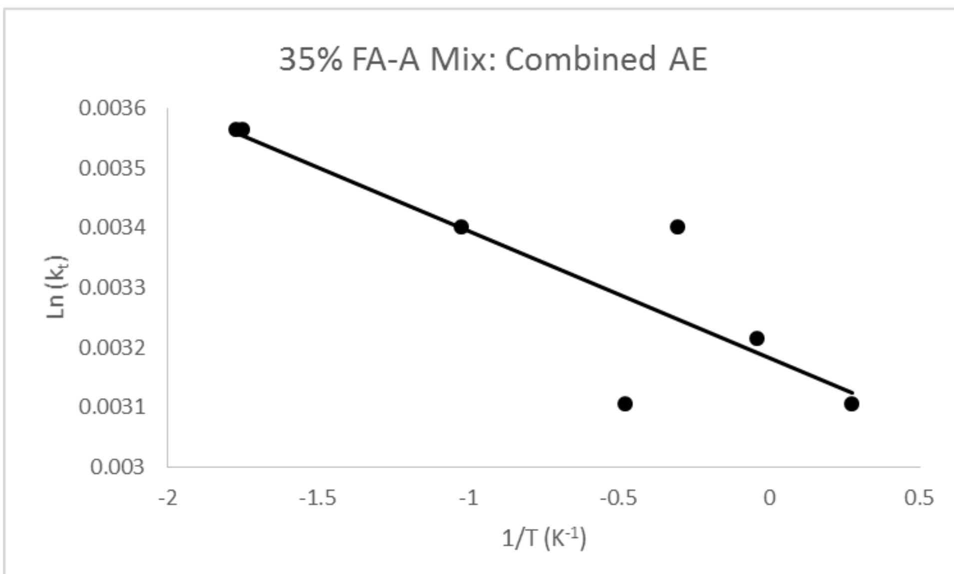

Figure 4.2: Arrhenius Plot for 35% FA-A Mix Based on 14 days data
Activation Energy of 35% FA-A Mix = 29706.04 J/Mol

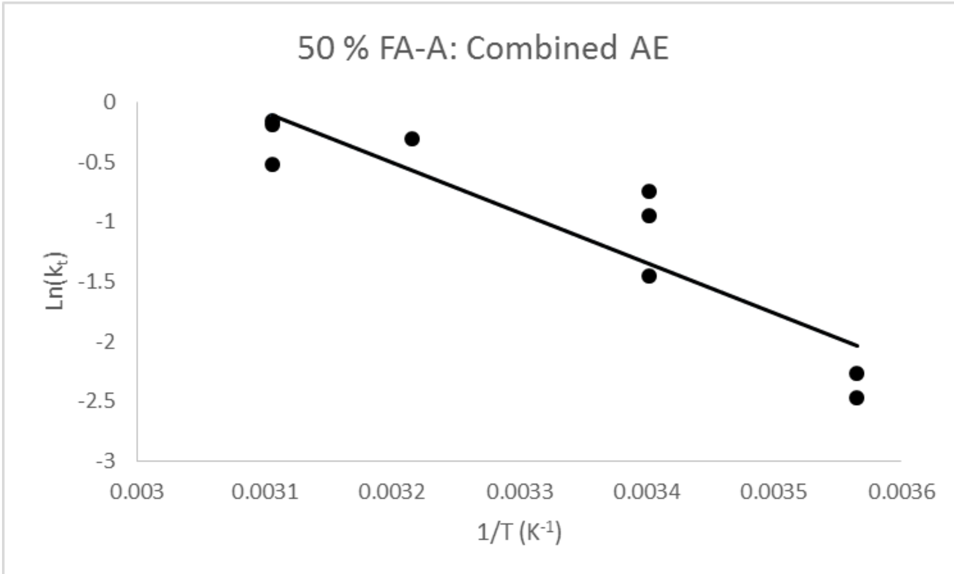

Figure 4.3: Arrhenius Plot for 50% FA-A Mix Based on 14 days data
Activation Energy of 50% FA-A Mix = 34889.02 J/Mol

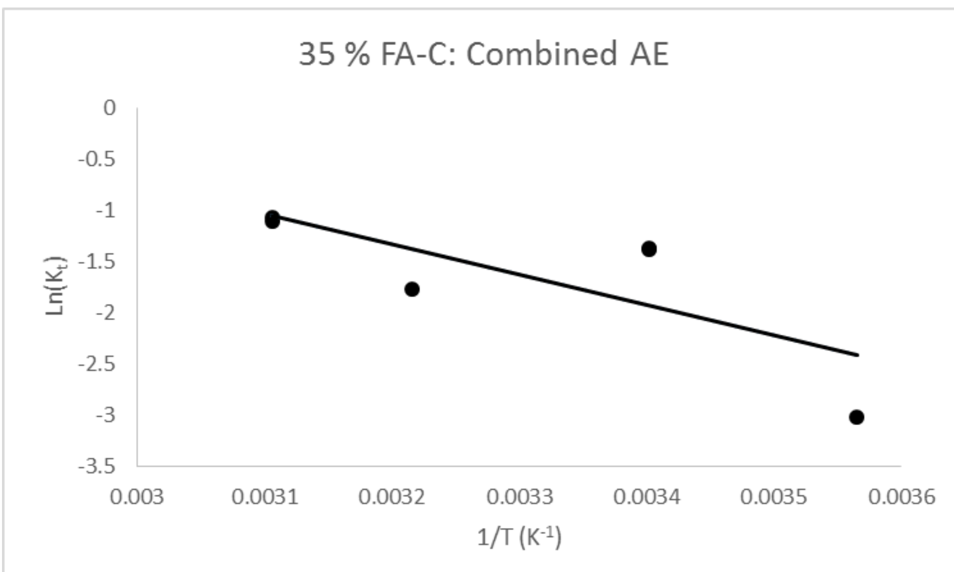

Figure 4.4: Arrhenius Plot for 35% FA-C Mix Based on 14 days data
Activation Energy of 35% FA-C Mix = 24627.51 J/Mol

The values of activation energy are shown in Table 4.3

Table 4.3: Activation Energy (ASTM C1074) Based on 14 days data

Mixture	AE (Trial 1) (J/Mol)	AE (Trial 2) (J/Mol)	AE (Trial 3) (J/Mol)	Combined AE (J/Mol)
Control Mix	37619.90	37672.75	NA	38067.55
35% FA-A Mix	33996.27	22438.81	NA	29706.04
50% FA- A Mix	43194.95	36346.59	6093.69	34889.02
35% FA-C Mix	27887.57	8712.37	NA	24627.51

Once the activation energy was determined, compressive strength test was performed on standard cylinders of size 10.2 X 20.3 cm (4in by 8in) as per ASTM C39. At each testing age, an average of three testing cylinders was reported as compressive strength. Temperature sensors were embedded in two cylinders to monitor the temperature profile during curing. Using the activation energy computed above for each mix, the age at which compressive strength test was performed on these standard cylinders were converted into equivalent age @ 23 ^{o}C. From the strength as determined from ASTM C39 and the corresponding equivalent age @ 23 ^{o}C, equation 3 was used to develop 14-day based maturity model for each of the mix. The results for conversion of age into equivalent age @ 23 ^{o}C and the corresponding compressive strength for all the mixes are given in the following tables. Furthermore temperature sensors were embedded in cylinder to maintain their temperature same as concrete cubes prepared for pullout testing. This is discussed in detail in section 4.

Table 4.4: Compressive Strength and Equivalent Age for Control Mix Based on 14 days data

Age	Equivalent Age @ 23 °C (Days)	Strength (MPa)
0	0.00	0.00
1	0.90	7.10
2	1.80	11.80
4	3.60	16.90
7	6.30	18.60
14	12.60	23.90

Table 4.5: Compressive Strength and Equivalent Age for 35% FA-A Mix Based on 14 days data

Age	Equivalent Age @ 23 °C (Days)	Strength (MPa)
0	0.00	0.00
1	0.92	4.80
2	1.84	7.10
4	3.68	9.70
7	6.45	12.60
14	12.90	18.00

Table 4.6: Compressive Strength and Equivalent Age for 50% FA-A Mix Based on 14 days data

Age	Equivalent Age @ 23 °C (Days)	Strength (MPa)
0	0.00	0.00
1	0.91	7.20
2	1.82	11.50
4	3.63	16.40
7	6.36	19.50
14	12.71	25.30

Table 4.7: Compressive Strength and Equivalent Age for 35% FA-C Mix Based on 14 days data

Age	Equivalent Age @ 23 °C (Days)	Strength (MPa)
0	0.00	0.00
1	0.93	5.60
2	1.87	12.30
4	3.74	19.50
7	6.54	24.20
14	13.08	38.30

From the equivalent age @ 23 °C and the compressive strength data provided in the above tables, prediction models were developed for each mix. These prediction models are shown in Figures 4.5 to 4.8.

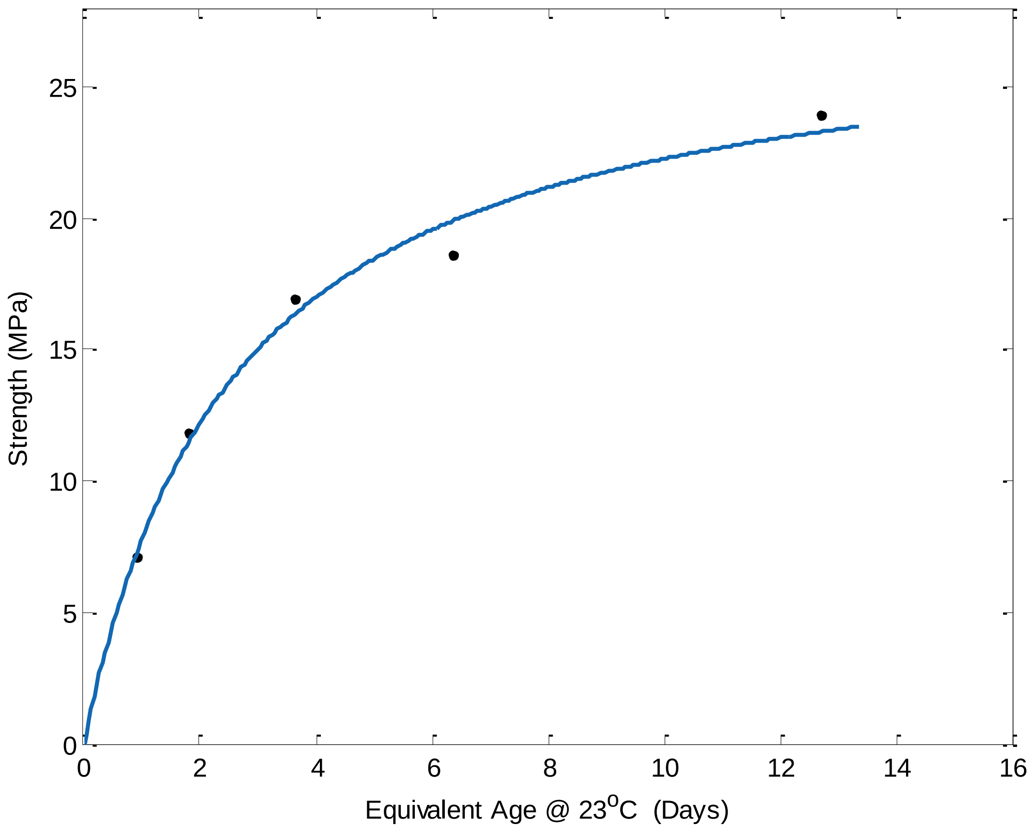

Figure 4.5: Strength vs Equivalent Age @ 23°C for Control Mix Based on 14 days data

The equation of the parabolic function of Figure 4.5 is the prediction model for the control mix based on the activation energy given in Table 4.3. This prediction model is given by

$$S_t = 10.84*t /(1+0.3861*t)$$

Where S_t is the compressive strength and ‘t’ is the equivalent age @ 23°C.

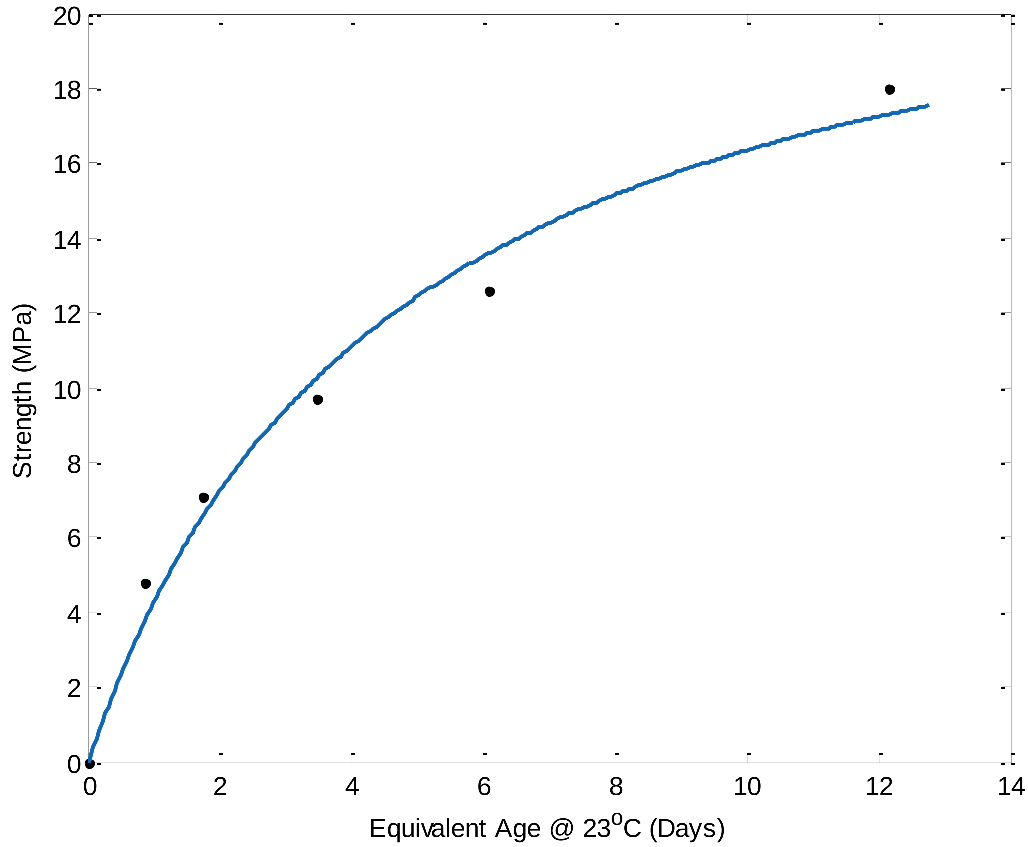

Figure 4.6: Strength vs Equivalent Age @ 23°C for 35% FA-A Mix Based on 14 days data

The equation of the parabolic function of figure 4.6 is the prediction model for 35% FA-A mix based on activation energy given in Table 4.3. This prediction model is given by

$$S_t = 4.89*t /(1+0.2048*t)$$

Where S_t is the compressive strength and ‘t’ is the equivalent age @ 23°C.

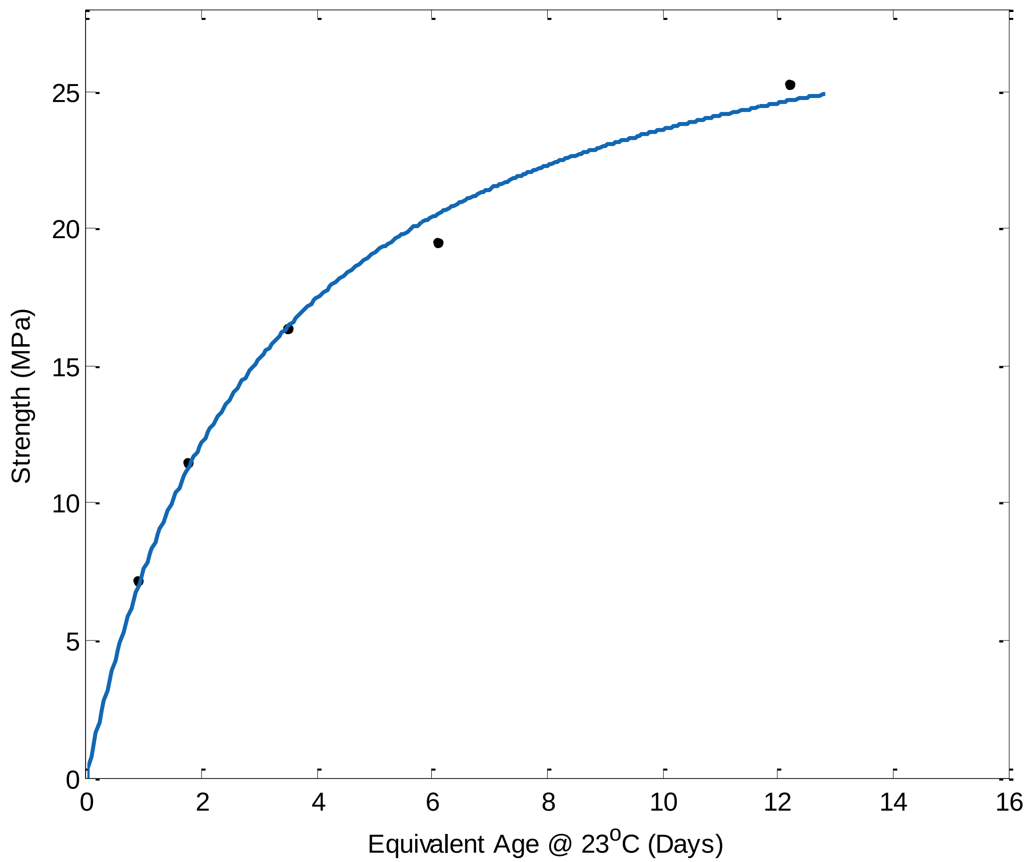

Figure 4.7: Strength vs Equivalent Age @ 23^{o}C for 50% FA-A Mix Based on 14 days data

The equation of the parabolic function of figure 4.7 is the prediction model for 50% FA-A mix based on activation energy given in Table 4.3. This prediction model is given by

$$S_t = 9.67*t /(1+0.3135*t)$$

Where S_t is the compressive strength and ‘t’ is the equivalent age @ 23^{o}C.

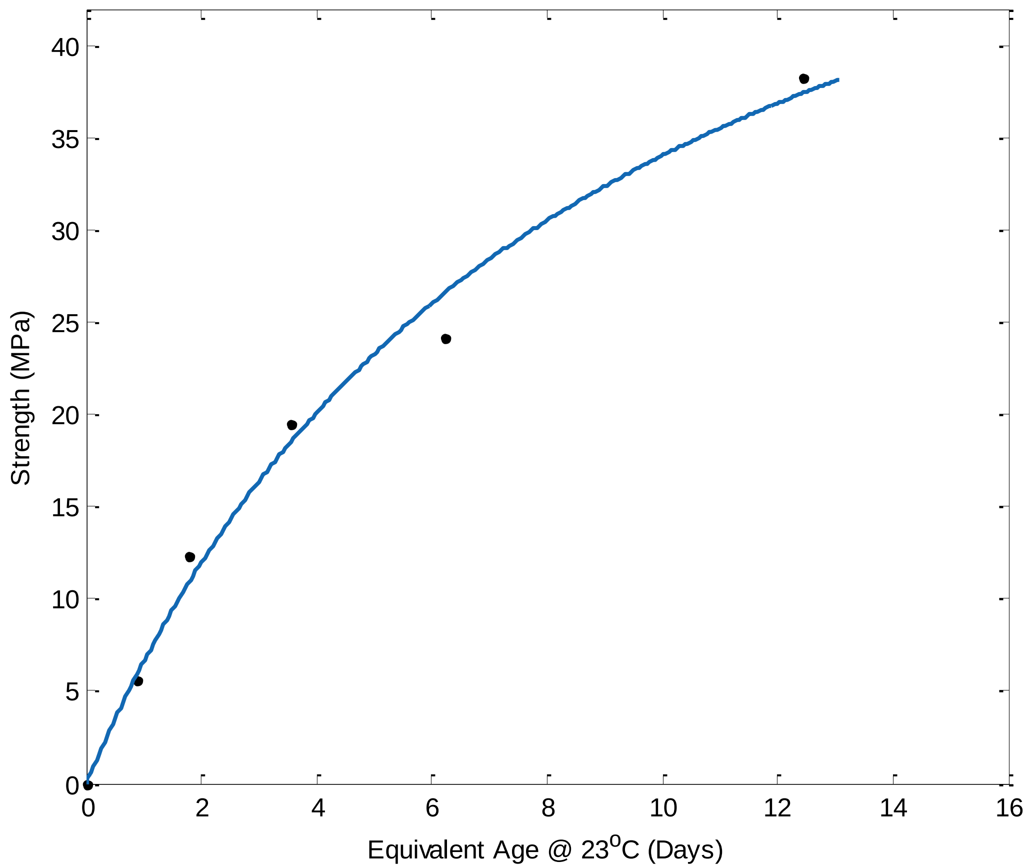

Figure 4.8: Strength vs Equivalent Age @ 23^{o}C for 35% FA-C Based on 14 days data

The parabolic function of the figure 4.8 is the prediction model for 35% FA-C mix based on activation energy given in Table 4.3. This prediction model is given by

$$S_t = 9.761*t /(1+0.2603*t)$$

Where S_t is the compressive strength and ‘t’ is the equivalent age @ 23^{o}C.

4.1.2 Activation Energy by Setting Time Method

The setting of mortar or concrete is the gradual transition from liquid to solid state. ASTM C403 was performed on mortar mixtures to determine the setting time. These results are tabulated in table 4.1. Setting time is defined as the time interval between initial setting and final setting. Mathematically, this can be represented as follows:

$$\boldsymbol{S_T = (F_S - I_S)} \qquad \textbf{Equation 4}$$

Where: S_T = Setting Time (mins)

F_S = Final Setting Time (mins)

I_S = Initial Setting Time (mins)

The initial and final setting time are determined using the Vicat's test. A 1mm diameter needle is allowed to penetrate freshly prepared cement paste for 30 seconds and the penetration is noted. The initial setting time is the time required for a penetration of 25mm to take place while the final setting time is when the needle does not penetrate into the paste. The hydration reaction starts as soon as cement comes in contact with water. As soon as the hydration reaction starts, the hydration temperature continues to increase until final setting time of concrete is reached. The final setting time relates to point at which stresses and stiffness begins to develop in freshly prepared concrete.

When concrete is cured at higher temperature, the hydration reaction will proceed at a faster rate thereby reducing the initial and final setting times. Conversely, concrete cured at lower temperature will increase the setting time of concrete. Thus, hydration reaction is the inverse of setting time. Mathematically, this can be represented as:

$$K_t = \frac{1}{S_T}$$ **Equation 5**

Where: K_t = Hydration Rate

Once the hydration constant is computed, the Activation Energy is determined in the same way as described in ASTM C1074 Annex A1. The activation energy computed by this approach is provided in the Table 4.8.

Table 4.8: Activation Energy by Setting Time Approach

Mixture	Activation Energy (J/Mol)
Control Mix	43328.04
35% FA-A Mix	40809.05
50% FA-A Mix	31373.57
35% FA-C Mix	37740.38

Based on the values of activation energy given in table 4.8, prediction models were developed. All the data to develop these models are shown in Table 4.9-4.12.

Table 4.9: Compressive Strength and Equivalent Age for Control Mix based on Setting Time Method

Age	Equivalent Age @ 23°C (Days)	Strength (MPa)
0	0.00	0.00
1	0.89	7.10
2	1.77	11.80
4	3.55	16.90
7	6.21	18.60
14	12.42	23.90

Table 4.10: Compressive Strength and Equivalent age for 35% FA-A mix based on Setting Time Approach

Age	Equivalent Age @ 23°C (Days)	Strength (MPa)
0	0.00	0.00
1	0.91	4.80
2	1.82	7.10
4	3.64	9.70
7	6.38	12.60
14	12.75	18.00

Table 4.11: Compressive Strength and Equivalent Age for 50% FA-A Mix based on Setting Time Method

Age	Equivalent Age @ 23°C (Days)	Strength (MPa)
0	0.00	0.00
1	0.92	7.20
2	1.83	11.50
4	3.67	16.40
7	6.42	19.50
14	12.84	25.30

Table 4.12: Compressive Strength and Equivalent Age for 35% FA-C Mix based on Setting Time Method

Age	Equivalent Age @ 23°C (Days)	Strength (Mpa)
0	0.00	0.00
1	0.90	5.60
2	1.80	12.30
4	3.60	19.50
7	6.31	24.20
14	12.61	28.30

From the equivalent age @ 23 °C and the compressive strength data provided in Tables 4.9 to 4.12, prediction models were developed for each mix. These prediction models are presented next.

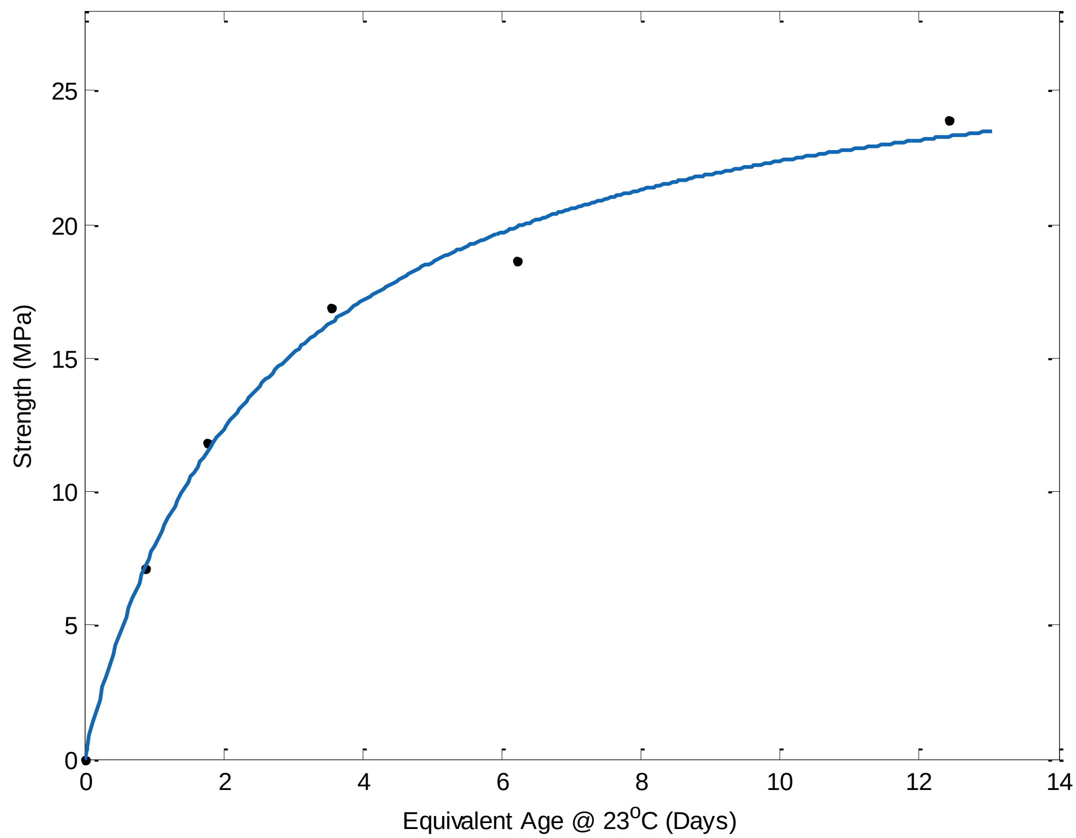

Figure 4.9: Strength vs Equivalent Age @ 23°C for Control Mix based on Setting Time Method

The equation of the curve above is the prediction model for Control mix based on activation energy found by setting time method. This prediction model is given by

$$S_t = 11*t / (1+0.3917*t)$$

Where S_t is the compressive strength and ‘t’ is the equivalent age @ 23°C.

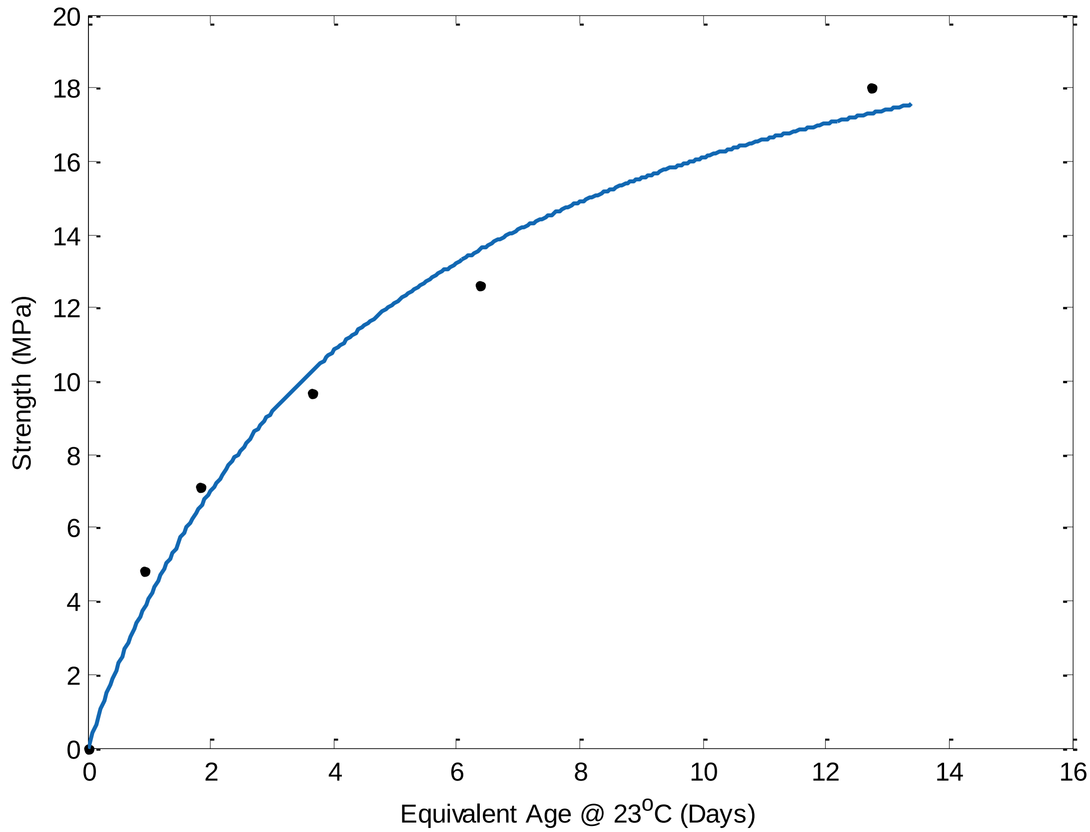

Figure 4.10: Strength vs Equivalent Age @ 23^{o}C for 35% FA-A Mix based on Setting Time Method

The equation of the curve above is the prediction model for 35% FA-A based on activation energy found by setting time method. This prediction model is given by

$$S_t = 4.944*t /(1+0.2070*t)$$

Where S_t is the compressive strength and ‘t’ is the equivalent age @ 23^{o}C.

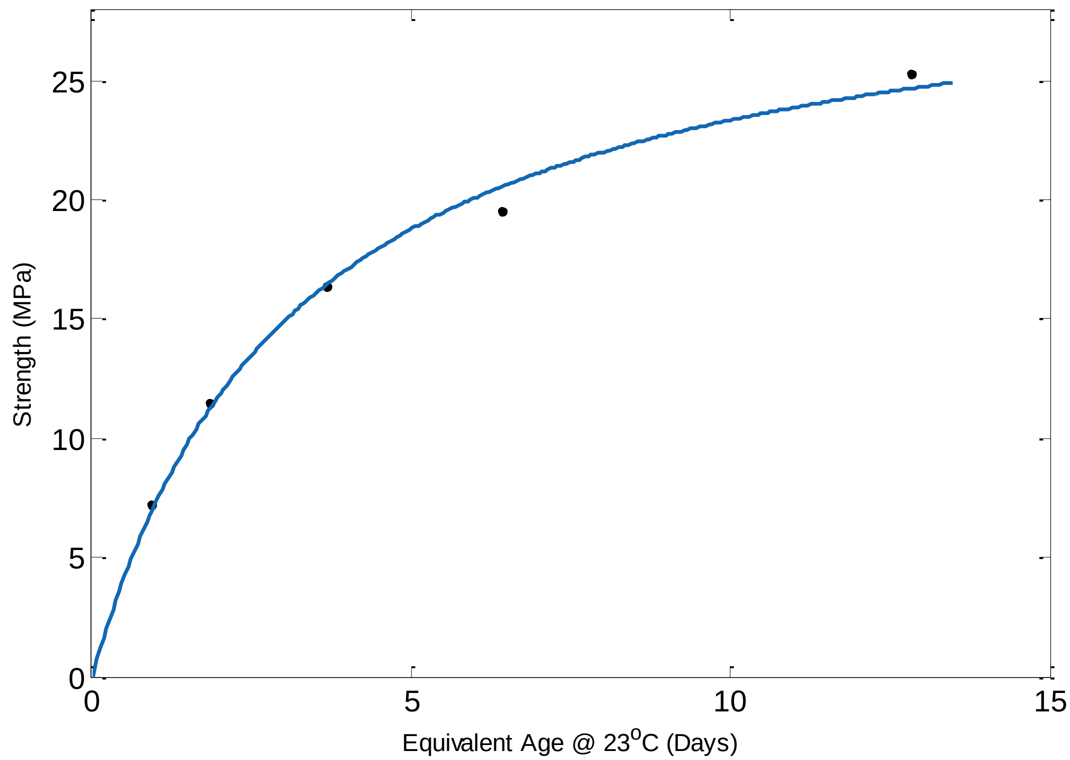

Figure 4.11: Strength vs Equivalent Age @ 23^{o}C for 50% FA-A Mix based on Setting Time Method

The equation of the curve above is the prediction model for 50% FA-A mix based on activation energy found by setting time method. This prediction model is given by

$$S_t = 9.576*t / (1+0.3104*t)$$

Where S_t is the compressive strength and 't' is the equivalent age @ 23^{o}C.

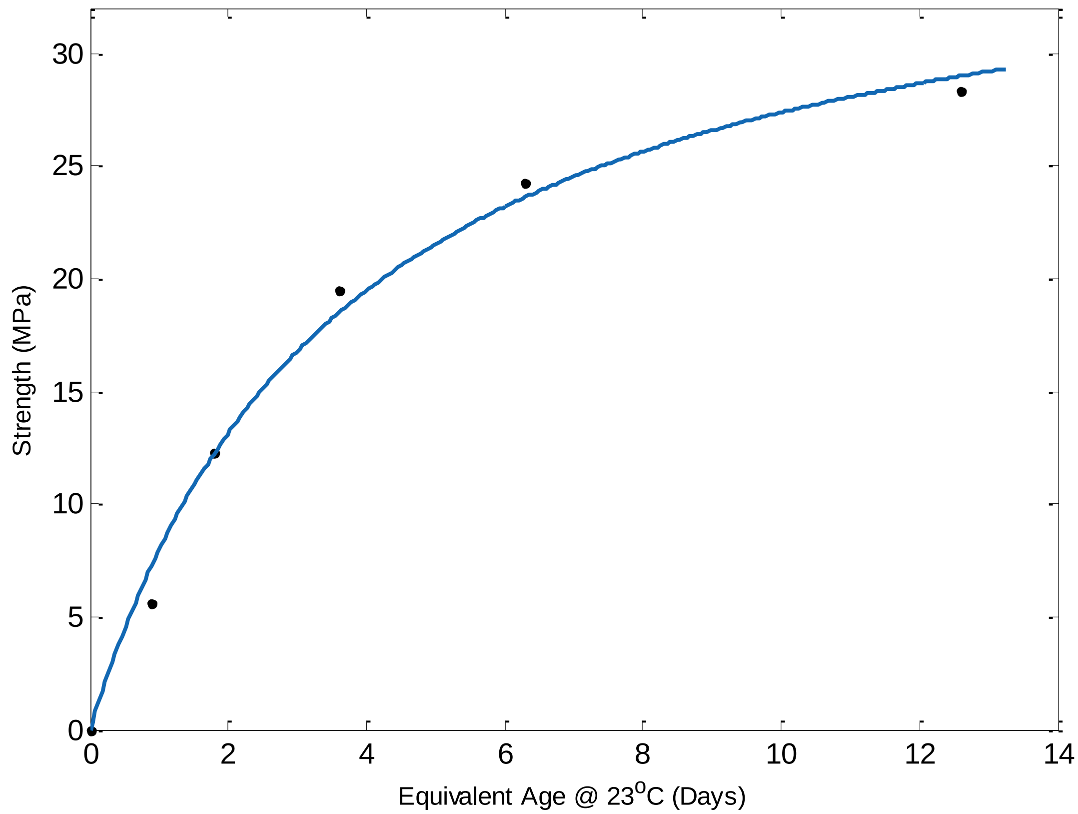

Figure 4.12: Strength vs Equivalent Age @ 23°C for 35% FA-A Mix based on Setting Time Method

The equation of the curve above is the prediction model for 35% FA-C mix based on activation energy found by setting time method. This prediction model is given by

$$S_t = 10.12*t / (1+0.2698*t)$$

Where S_t is the compressive strength and 't' is the equivalent age @ 23°C.

4.1.3 Activation Energy by Constant S_{uc} Approach

In most situations, concrete mixtures are designed to have certain amount of ultimate compressive strength. Hence, the mix design process of concrete focuses on attaining a required amount of compressive strength known as the ultimate strength. In section 4.1.1, the best fit trend line gives variable value of ultimate strength depending on the curing conditions. Ideally, there should be one limiting strength value (ultimate strength) for concrete mixtures irrespective of the temperature at which they were cured. In this approach, the activation energy is calculated as per ASTM C1074 just as in section 4.1.1. However, instead of variable S_u achieved due to best fit trend line, the limiting strength was kept constant (S_{uc}) and then the best fit line provided the values of rate constant. The values of limiting strength and rate constant are given in Table 4.13

It must be noted that this approach is similar to the one employed in section 4.1.1. However, there is a conceptual difference between the two approaches. While the approach in section 4.1.1 will yield multiple values of limiting strength based on function of the curing conditions, this approach yields one value of limiting strength irrespective of curing conditions.

Table 4.13: Rate Constants using Constant S_{uc} Approach

Mixture	Trial	S_{uc} (MPa)	7.5°C(45 °F) k_t (day^{-1})	21°C (70 °F) k_t (day^{-1})	38°C(100 °F) k_t (day^{-1})	49 °C(120°F) k_t (day^{-1})
Control Mix	1	31.30	0.207	0.719	1.492	1.760
	2	29.20	0.261	0.625	-	1.419
35% FA-A Mix	1	28.30	0.047	0.228	0.677	0.923
	2	29.80	0.036	0.151	-	0.939
	3	28.10	0.042	0.242	-	0.732
50% FA-A Mix	1	53.20	0.042	0.140	0.499	0.718
	2	46.60	0.073	0.187	-	0.968
	3	50.00	-	0.132	-	0.720
	4	28.10	-	0.501	-	1.849
35% FA-C Mix	1	42.70	0.039	0.135	0.163	0.696
	2	41.00	-	0.111	-	0.467
	3	44.50	-	0.099	-	0.393

From the rate constants provided in Table 4.13 the value of activation energy was determined based on all the trials. This value of activation energy is denoted by ‘Combined AE’ in Table 4.14.

Table 4.14: Activation Energy by Constant S_{uc} Approach

Mixture	AE (Trial 1) (J/Mol)	AE (Trial 2) (J/Mol)	AE (Trial 3) (J/Mol)	AE (Trial 4) (J/Mol)	Combined AE (J/Mol)
Control Mix	38666.89	29738.30	NA	NA	34720.67
35% FA-A Mix	46511.35	NA	NA	NA	46511.35
50% FA-A Mix	52556.75	46774.40	47547.37	36381.84	49415.46
35% FA-C Mix	45363.32	40423.53	38679.25	NA	42692.49

The addition of fly ash slows the rate of hydration reaction in concrete. This is also evident in table 4.1 where the setting time of concrete increases with increase in fly ash content. Thus, it is expected that increasing fly ash content will lead to lower value of activation energy. The results of Table 4.14 that are based on the activation energy computed by the constant S_{uc} approach do not represent the effect of fly ash on concrete. Hence, this approach was judged to not represent well the hydration of these mixtures.

<u>4.2 Actual in-place strength due to mass concrete effects</u>

The developed prediction models provide engineers the opportunity to predict the in place compressive strength of concrete members.

The degree of accuracy of these prediction models depend upon how the predicted values from these models compare against the actual in-place strength after considering the mass effect in concrete structures. This in-place strength also known as match cured strength is the most accurate estimate of in place strength of concrete members.

Temperature sensors are inserted in concrete structure at specific locations to capture the mass effect. These sensors capture the actual temperature profile inside the structure and transmit the data on to a micro-controller. The micro-controller, with the help of a software replicates the same temperature profile inside the standard concrete cylinders (as required in ASTM C39) with the help of thermocouples. Compression test is then performed on these cylinders at required ages to determine the actual in place strength. The process is called match curing simple because the temperature profile of cylinders is matched with that of the actual structure during curing.

The challenge now was to build a structure large enough to observe the mass effect of concrete. For detailed analysis, two types of structures were built: a concrete block of 0.6 x 0.6 x 1.8 m (2 x 2 x 6 ft) and concrete slab 2.4 x 2.4 x 0.18 m (8ft x 8ft x 7 in). Due to logistical issues, the concrete slab was developed only for the control mix and 50% FA-A mix.

4.2.1 Block Testing

Since the research focused on analyzing 4 concrete mixes, 4 concrete blocks were cast with each block representing each mix. It is important to note that the concrete blocks were used to serve two purposes: to simulate the mass effect and for performing pullout test. The pullout test is a non-destructive test and is explained in detail in section 4.3. In this section, the use of concrete block to simulate mass effect will be discussed.

Temperature sensors (also known as iButtons) were used to map the temperature profile of the concrete block. These temperature sensors were inserted at different locations in the block. For the purpose of maturity, the data from the sensor located at 2.54 cm from surface of block with is relayed to micro-controller. The micro-controller matches the temperature of the cylinders with this temperature with the help of thermocouple. This thermocouple should be inserted at mid-depth of the cylinder with a 1in cover from the edges for accurately simulating the temperature in the cylinder. The activation energy for the mixtures have been previously determined and with the temperature data from iButton, the equivalent age of the block is can be computed using equation 2 given in chapter 2. With the equivalent age, the compressive strength is predicted from the prediction models developed above.

The match cured strength is determined at the ages of 2, 4 and 7 days. At each age, three cylinders are tested and the average is reported as the compressive strength. This strength is the best estimate of in place compressive strength and is known as match cured strength and the value obtained from prediction model will be compared against this. Although the 28-day match cured strength was not available, it was required for purpose of comparisons. Equation 3 was used to predict the match cured strength at 28 days. The existing strength values were substituted as S_t and their corresponding equivalent ages @ 23^{o}C were computed from the measured temperature profile. A trend line was fitted to this data and from this best fit tend line, the values of limiting strength S_u and rate constant ‘k’ were determined and attempt was made to predict the 28-day match cured strength. The results of match curing are presented in Table 4.15

Table 4.15: Match Cured Strength-Control Mix Block

Actual Age (Days)	Match Cured Strength (MPa)
0	0.00
2	19.33
4	23.85
7	26.51
28	29.84

Table 4.16: Match Cured Strength-35% FA-A Mix Block

Actual Age (Days)	Match Cured Strength (MPa)
0	0.00
2	12.54
4	16.63
7	19.34
28	23.09

Table 4.17: Match Cured Strength-50% FA-A Mix Block

Actual Age (Days)	Match Cured Strength (MPa)
0	0.00
2	14.92
4	19.48
7	22.42
28	26.41

Table 4.18: Match Cured Strength-35% FA-C Mix Block

Actual Age (Days)	Match Cured Strength (MPa)
0	0.00
2	23.68
4	30.23
7	34.29
28	39.62

4.2.2 Slab Testing

Due to logistical issues, the concrete slabs were prepared only for two mixtures, the control mix and 50% FA-A mix. Similar to blocks, even the slab were used for match curing as well as pullout testing. The use of slabs for pullout testing will be discussed in section 4.3. In the slabs, the temperature sensors located at 5.08 cm from top surface around middle third of the slab were used for maturity calculation. The match cured strength test was performed at 2, 4 and 7 days. The process of predicting the match cured strength at 28 days is exactly the same as described for concrete blocks.

Table 4.19: Match Cured Strength-Control Mix Slab

Actual Age (Days)	Match Cured Strength (MPa)
0	0.00
2	19.29
4	25.40
7	29.39
28	34.86

Table 4.20: Match Cured Strength-50% FA-A Slab

Actual Age (Days)	Match Cured Strength (MPa)
0	0.00
2	10.69
4	14.90
7	17.92
28	22.48

4.3 Pullout Testing

Pullout test is a non-destructive test. Similar to match curing, the pullout test is used to determine the in place compressive strength of concrete. The pullout test measures the force needed to extract an embedded insert from concrete mass (Carino 2003). This force is known as Pullout force. This pullout force is then used to determine the compressive strength of concrete by using some previously established compressive strength vs pullout force relationships.

Concrete cubes 20.32 cm (8 in) size, used previously for determining the actual in place strength of concrete blocks, were also used to develop the compressive strength vs pullout load relationship. To achieve this, sufficient concrete cubes were casted such that at the required age, one cube was used to determine the actual in place strength while pullout test was performed on other cube. Temperature sensors were inserted at height of 2.54 cm (1 in) from bottom surface of the cube at the center. These sensors helped in maintaining the temperature of cubes and the cylinders. Pullout inserts were embedded in each of the four sides of the cube. This was done to prevent any radial cracking. The testing was conducted at age of 1,2,4,7 and 14 days Upadhyaya 2008).

4.3.1 Compressive Strength vs Pullout Force Correlation

Compressive strength has been related to the pullout force with exponential functions. The manufacture of pullout testing apparatus provide such relationships for use. . However, in this research such relationship was developed for the specific mixtures used. The general form of such relation as given in ACI 228.1R-03 is:

$$C = a * P^b \qquad \textbf{Equation 6}$$

Where, C = Compressive Strength (MPa)

a,b = Regression Constants, a (MPa)

P = Pullout Force (kN)

The results from pullout testing are provided below:

Table 4.21: Pullout Force and Compressive Strength for Control Mix

Age (Days)	Pullout Force (kN)	Standard Cured Strength (MPa)
0	0.00	0.00
1	8.45	7.10
2	12.50	11.80
4	15.63	16.90
7	17.90	18.60
14	21.61	23.90

Table 4.22: Pullout Force and Compressive Strength for 35% FA-A Mix

Age (Days)	Pullout Force (kN)	Standard Cured Strength (MPa)
0	0.00	0.00
1	7.19	4.80
2	9.40	7.10
4	10.59	9.70
7	13.41	12.60
14	18.03	18.00

Table 4.23: Pullout Force and Compressive Strength for 50% FA-A Mix

Age (Days)	Pullout Force (kN)	Standard Cured Strength (MPa)
0	0.00	0.00
1	10.44	7.20
2	13.97	11.50
4	17.36	16.40
7	19.58	19.50
14	25.45	25.30

Table 4.24: Pullout Force and Compressive Strength for 35% FA-C Mix

Age (Days)	Pullout Force (kN)	Standard Cured Strength (Mpa)
0	0.00	0.00
1	7.16	5.60
2	12.86	12.30
4	18.30	19.50
7	20.84	24.20
14	22.49	38.30

Based on the data given in tables 4.21 to 4.24 and equation 6, the relationships between compressive strength and pullout force were determined.

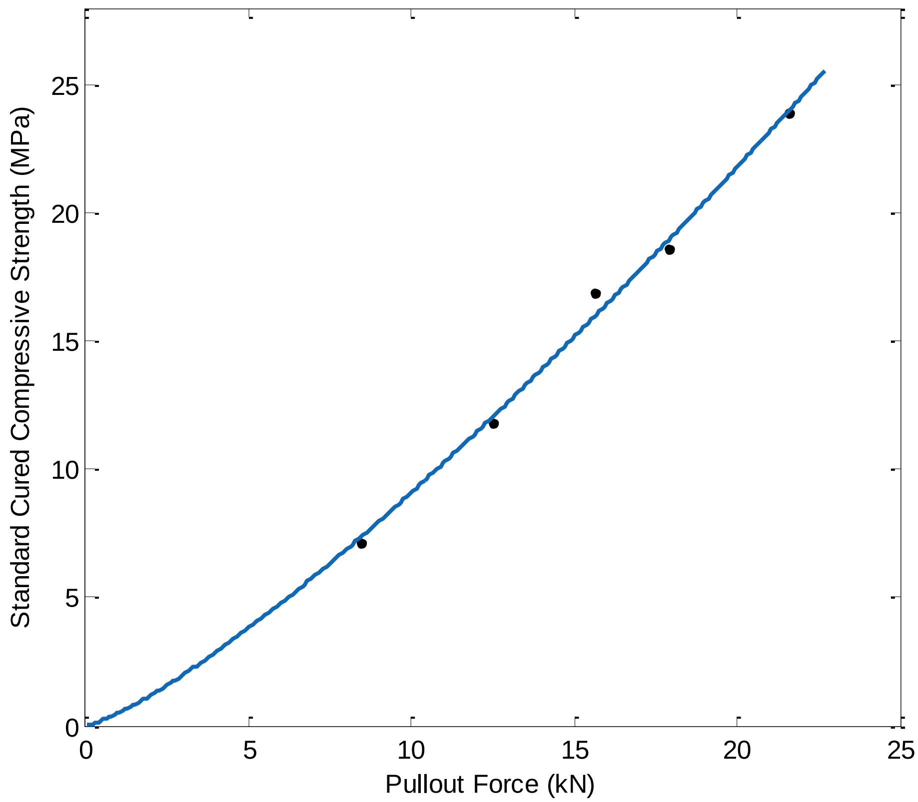

Figure 4.13: Compressive Strength vs Pullout Force for Control Mix

The correlation between Compressive strength and Pullout load is given by

$$\mathbf{C = 0.5009*P^{1.259}}$$

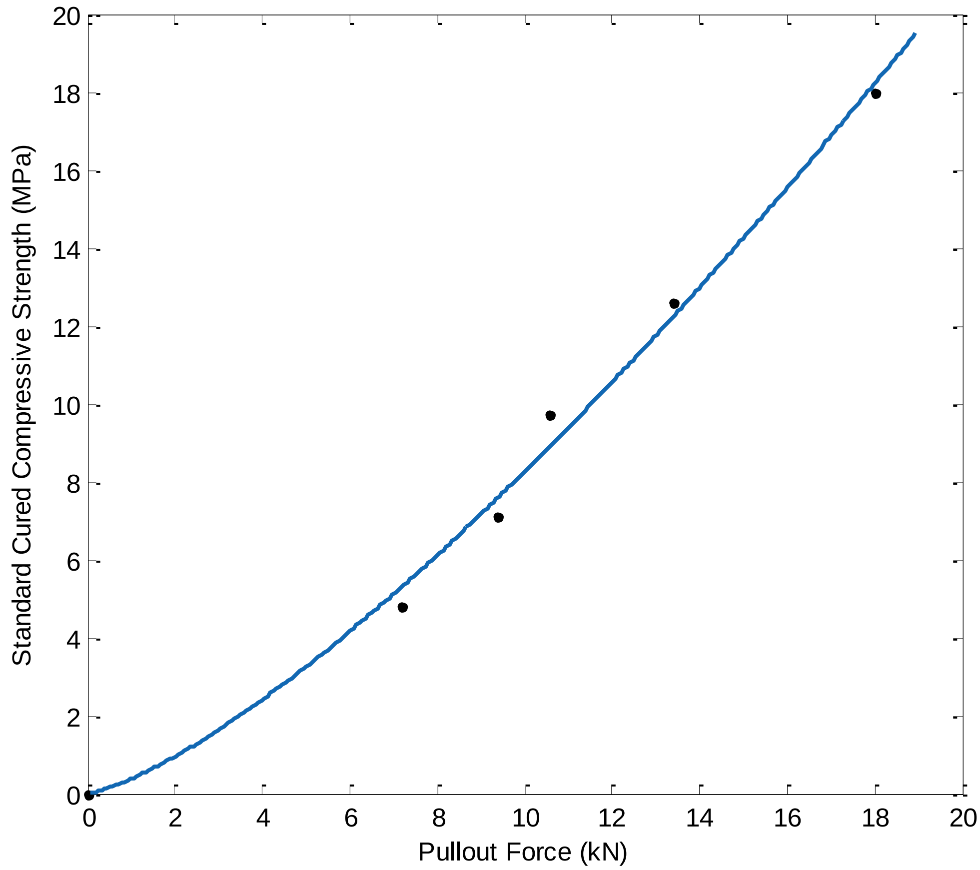

Figure 4.14: Compressive Strength vs Pullout Force for 35% FA-A Mix

The correlation between Compressive strength and Pullout load is given by

$$\mathbf{C = 0.3733 * P^{1.345}}$$

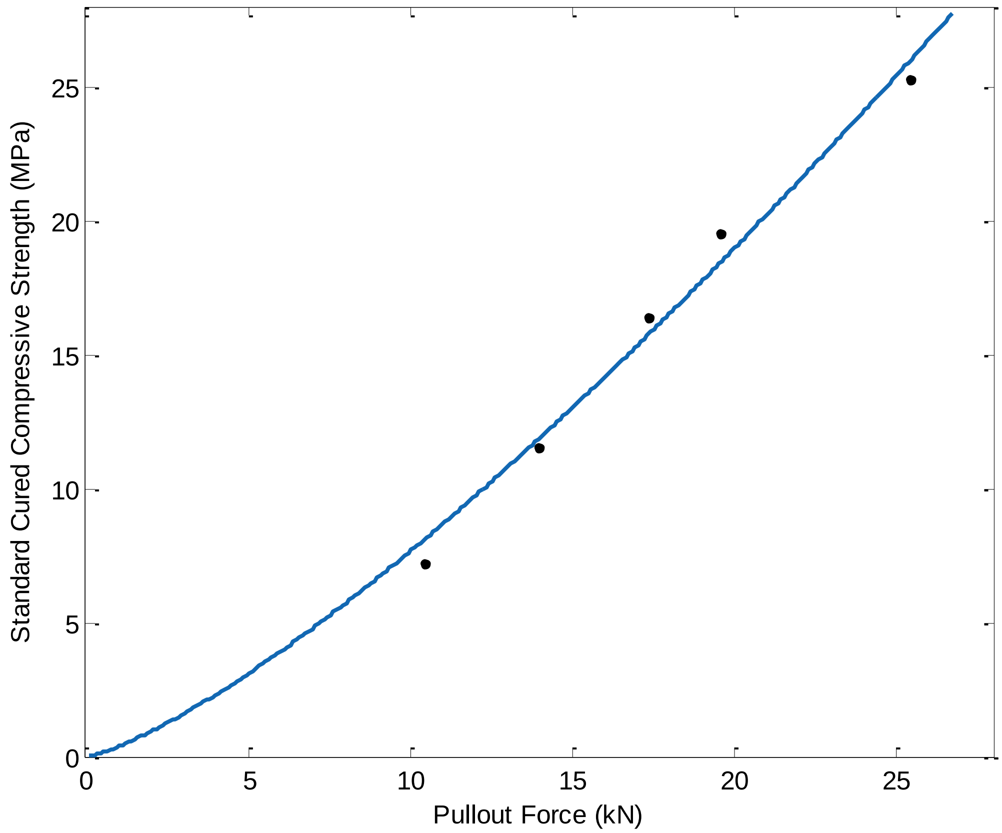

Figure 4.15: Compressive Strength vs Pullout Force for 50% FA-A Mix

The correlation between Compressive strength and Pullout load is given by

$$\mathbf{C = 0.3755*P^{1.309}}$$

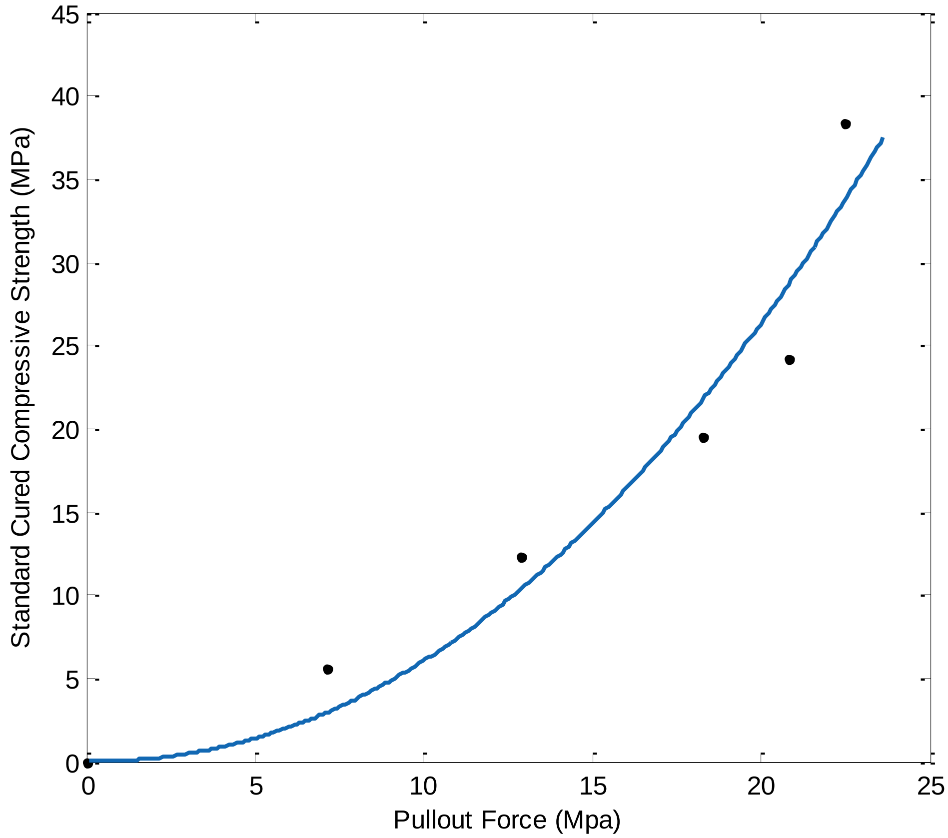

Figure 4.16: Compressive Strength vs Pullout Force for 35% FA-C Mix

The correlation between Compressive strength and Pullout load is given by

$$\mathbf{C = 0.04584*P^{2.121}}$$

4.3.2 Pullout Tests on concrete blocks

The concrete blocks of size 0.6 x 0.6 x 1.8 m that were casted for match curing as described in section 4.2 were also used for pullout testing. 12 Pullout inserts were embedded on each of the longer side. Thus, there were 24 inserts in total. ASTM C900 provides guidelines with regards to minimum distance between inserts, clear cover between the edges and inserts etc. Following these guidelines, the inserts were placed at 0.145 m distance center to center and 0.115 m from the edge. The pullout inserts extended 2.54 cm into the concrete surface. The pullout test were performed at 2, 4 and 7 days using the "SureCure" system (Upadhyaya, 2008).

4.3.3 Pullout testing on concrete slabs

The concrete slabs that were casted for match curing of size 2.4 x 2.4x 0.18 m were also used for pullout testing. Due to logistical issues, the slabs were casted only for control mix and 50% FA-A mix. The inserts were embedded in slab just the same way as they were embedded in block as described above. The pullout tests were performed at 2, 4 and 7 days. From the pullout forces, the compressive forces were estimated from the models developed above

(Upadhyaya, 2008). The results of the pullout test are provided in Table 4.25 to 4.30.

Table 4.25: Pullout Force and estimated Compressive Strength for Control Mix Block

Age (Days)	Pullout Force (kN)	Estimated Strength (MPa)
0	0.00	0.00
2	17.18	18.00
4	18.53	19.73
7	21.53	23.84

Table 4.26: Pullout Force and Compressive Strength for Control Mix Slab

Age (Days)	Pullout Force (kN)	Estimated Strength (MPa)
0	0.00	0.00
2	16.33	16.82
4	19.03	20.40
7	20.69	22.73

Table 4.27: Pullout Force and Compressive Strength for 35% FA-A Block

Age (Days)	Pullout Force (kN)	Estimated Strength (MPa)
0	0.00	0.00
2	10.75	9.16
4	11.09	9.51
7	13.64	12.49

Table 4.28: Pullout Force and Compressive Strength for 50% FA-A Block

Age (Days)	Pullout Force (kN)	Estimated Strength (MPa)
0	0.00	0.00
2	16.60	14.85
4	17.50	15.91
7	18.21	16.75

Table 4.29: Pullout Force and Compressive Strength for 50% FA-A Slab

Age (Days)	Pullout Force (kN)	Estimated Strength (Mpa)
0	0.00	0.00
2	11.79	9.50
4	14.83	12.78
7	17.10	15.44

Table 4.30: Pullout Force and Compressive Strength for 35% FA-C Block

Age (Days)	Pullout Force (kN)	Estimated Strength (Mpa)
0	0.00	0.00
2	20.35	27.48
4	22.99	35.44
7	24.28	39.82

4.4 Field Curing

Concrete cylinders were also field cured to compare how the field cured values compare against the match cured values and strength estimated from pullout forces (Upadhyaya 2008). The field cured cylinders did not simulate the temperature profile in the concrete blocks. Field curing represents traditional method of determining in place compressive strength of concrete. Field cured cylinders were tested at 2, 4 and 7 days. At each age, three cylinders were broken and the average of the three was reported as the compressive strength. The results are provided below.

Table 4.31: Field Cured Strength for Control Mix Block

Age (Days)	Field Cured Strength (MPa)
0	0.00
2	8.60
4	13.90
7	18.00

Table 4.32: Field Cured Strength for Control Mix Slab

Age (Days)	Field Cured Strength (MPa)
0	0.00
2	11.80
4	15.80
7	21.70

Table 4.33: Field Cured Strength for 35% FA-A Mix Block

Age (Days)	Field Cured Strength (MPa)
0	0.00
2	5.60
4	9.50
7	11.90

Table 4.34: Field Cured Strength for 50% FA-A Mix Block

Age (Days)	Field Cured Strength (MPa)
0	0.00
2	8.00
4	15.30
7	17.90

Table 4.35: Field Cured Strength for 50% FA-A Mix Slab

Age (Days)	Field Cured Strength (MPa)
0	0.00
2	8.70
4	14.90
7	17.10

Table 4.36: Field Cured Strength for 35% FA-C Mix Block

Age (Days)	Field Cured Strength (MPa)
0	0.00
2	12.00
4	20.70
7	25.50

Chapter 5 Exploring Alternative Approaches for Maturity Modeling

The Pull-out testing is a reliable method for estimating in place compressive strength. The pullout tests were performed on all concrete mixtures at the age of 2, 4 and 7 days. Using this method the in place compressive strength was estimated for each concrete mixture using the correlations of pullout force vs compressive strength given in Figures 4.17 to 4.20. Testing was conducted on two type of structural elements, concrete blocks and slabs. Slabs were prepared for the control and the 50% FA-A mixture. To take into account the mass concrete effects on maturity prevalent in large (mass) concrete structures, it was important to convert the actual ages into equivalent ages @ 23°C. The activation energy as computed in Table 4.3 was used to perform this conversion. From the equivalent ages, the in place compressive strength was predicted for each mixture using the models shown in Figures 4.5 to 4.8. The pullout force-compressive strength relationship developed in this research was based on the 14-day strength data. In the previous study (Upadhyaya, 2008), this relationship was based on the 28-day strength data. Table 5.1 compares the results from both approaches along with the match cured strength. Table 5.2 presents the error from the 14-day and the 28-day pullout correlations in relation to the match cured strength.

For the control mix, there is only a small difference between predicted values from 14-day pullout correlations and 28-day pullout correlations. For example, in the case of the control mix block at age of 2 days, the 14-day pullout correlation predict a strength of 18.0 MPa while the 28-day pullout correlation predict it to be 17.90 MPa. For the control mix block at the age of 2 days, the 14-day pullout correlations under-predict the strength by 1.40% while the 28-day pullout under-predict by 1.50%. In the case of the control mix slab at the age of 4 days, the 14-day pullout based prediction under-predicts strength by 4.60% while the 28-day based prediction under-predict by 4.80%. The 14-day pullout correlation offer small improvement over the 28-day pullout correlation.

For the 35% FA-A mix at the ages of 2, 4 and 7 days, the strength predicted by the 14-day pullout correlation is 9.16 MPa, 9.51 MPa and 12.49 MPa while the 28-day pullout correlation predict a strength of 9.10 MPa, 9.50 MPa and 12.40 MPa, respectively. Thus, the difference in predicted values is very small. Overall, the 14-day pullout under-predicts by 3.24%, 7.39% and 6.71% at the ages of 2, 4 and 7 days respectively while the 28-day pullout under-predicts the corresponding values by 3.30%, 7.40% and 6.80%. As observed in the case of the control mix, the 14-day pullout correlation offer small improvement over the 28-day pullout correlation.

This is also the case with the 50% FA-A mix. The under-prediction for the concrete block is 3.60% by both the 14-day and 28-day pullout correlations at the age of 4 days, while for the slab the 14-day pullout correlation under-predicts by 0.80% at the age of 2 days, and the 28-day pullout correlation under-predicts the corresponding value by 1.00%.

However, for the 35% FA-C mix, the 14-day pullout correlation over-predict in-place strength at every testing age while the 28-day pullout correlation under-predict the in-place testing age at every testing age.

Table 5.1: Comparison of Match Cure Strength with Predicted Strength from the 14-day and the 28-day Pullout Correlations

Mixture	Concrete Element	Actual Days	Equivalent Age @ 23°C	Match Cure Strength (MPa)	Strength Predicted by 28-Day Pullout Correlation (MPa)	Strength Predicted by 14-day Pullout Correlation (MPa)
Control Mix	Block	2	3.43	19.40	17.90	18.00
		4	5.99	23.70	19.60	19.73
		7	8.38	26.60	23.40	23.84
	Slab	2	1.72	19.50	16.80	16.82
		4	2.88	25.0	20.20	20.40
		7	4.66	29.60	22.30	22.73
35 % FA-A Mix	Block	2	2.40	12.40	9.10	9.16
		4	4.60	16.90	9.50	9.51
		7	7.19	19.20	12.40	12.49
50% FA-A Mix	Block	2	2.42	14.90	14.80	14.85
		4	4.59	19.50	15.90	15.91
		7	7.19	22.40	16.80	16.75
	Slab	2	1.58	10.30	9.30	9.50
		4	3.17	15.60	12.70	12.78
		7	5.02	17.60	15.40	15.43
35 % FA-C Mix	Block	2	3.42	23.60	22.90	27.47
		4	6.02	30.40	26.60	35.44
		7	9.21	34.20	28.40	39.82

Table 5.2: Percent strength prediction differences between match cured versus the 14-day and the 28-day Pullout correlations

Mixture	Concrete Element	Actual Days	28-day Pullout Correlation (%)	14-day Pullout Correlation (%)
Control Mix	Block	2	-1.50	-1.40
		4	-4.10	-3.97
		7	-3.20	-2.76
	Slab	2	-2.70	-2.68
		4	-4.80	-4.60
		7	-7.30	-6.87
35 % FA-A Mix	Block	2	-0.10	-3.24
		4	-3.60	-7.39
		7	-6.80	-6.71
50 % FA-A Mix	Block	2	-0.10	-0.05
		4	-3.60	-3.59
		7	-5.60	-5.65
	Slab	2	-1.00	-0.80
		4	-2.90	-2.82
		7	-2.20	-2.17
35 % FA-C Mix	Block	2	-0.70	3.87
		4	-3.80	5.04
		7	-5.80	5.62

It is also important to compare how the 14-day based maturity model predict the in-place strengths against the in-place strength estimated by the 14-day pullout correlations. Table 5.3 provides this comparison.

For the control concrete mix block, at the age of 2 days, the strength estimated by the pullout correlation is 18.00 MPa while the strength predicted from the 14-day maturity model is 15.99 MPa. The strength estimated at 4 days is practically the same by both methods. At 7 days the pullout correlation estimates a strength of 23.84 MPa while the 14-day model estimate 21.44 MPa. Thus, as compared to the values from the pullout correlation, the 14-day maturity models under-predict by 11.67% at the age of 2 days, 0.68% at age of 4 days and 10.00% at age of 7 days. There is a wide variability in predicting the in place strength of the control mix slab. At the ages of 2, 4 and 7 days, the strength predicted from 14-day maturity models are 11.20 MPa, 14.78 MPa and 18.04 MPa respectively while the corresponding values from pullout correlations are 16.82 MPa, 20.40 MPa and 22.73 MPa. Thus, when compared with values from the pullout correlation, the 14-day maturity models under-predict by 33.40% at age of 2 days, 27.50% at age of 4 days and 20.63% at age of 7 days. Again, the 14-day maturity models consistently predict lower values of in-place compressive strength for the control mix.

The level of under-predicting concrete strength is much higher for the case of concrete slab. This has to do with the lack of mass effects on maturity on slabs versus concrete blocks. .

In the case of the 35% FA-A block, the strength predicted from the 14-day maturity models are 7.98 MPa, 11.72 MPa and 14.38 MPa for the ages of 2, 4 and 7 days respectively while the corresponding values from the pullout correlation are 9.16 MPa, 9.51 MPa and 12.49 MPa. The values from the 14-day maturity models are more accurate for these age groups. This is because the strength at these ages are 12.40 MPa, 16.90 MPa and 19.20 MPa (Table 5.1) and hence, except at the age of 2 days, the 14-day pullout correlations have given lower estimates of in-place strength   The 14-day maturity models have estimated higher strength at age of 4 and 7 days thereby improving the accuracy of prediction.

For the 50% FA-A slab mix results, the 14-day based maturity method consistently predicts higher values of in-place compressive strength at all ages than the pullout testing. This is reflected in the case of the 50% FA-A block as well except at the age of 2 days. For the block, the strength predicted at 4 days by the 14-day maturity model is 18.43 MPa which is 15.82% higher than the 15.91 MPa estimated strength by the pullout test. At 7 days, the strength predicted from the 14-day maturity is 20.93 MPa which is 25% more than the 16.75 MPa estimated by the pullout test. For the slab, at ages of 2, 4 and 7 days, the strength estimated by the 14-day models are 10.39 MPa (9.4% more than the pullout test), 15.55 MPa (21.65% more than the pullout test) and 19.04MPa (23.40 % more than the pullout test) respectively. The match cured strength for 50% FA-A block at ages 2, 4 and 7 can be found from table 5.1 and they are 14.90 MPa, 19.50 MPa and 22.40 MPa respectively. For slab, the strength at 2, 4 and 7 days are 10.30 MPa, 15.60 MPa and 17.60 MPa. Thus, the 14-day maturity models have been successful in reducing the degree of under-prediction in 50% FA-A mix.

In the case of the 35% FA-C block, the 14-day based maturity models consistently under predict the in place compressive strength. The 14-day maturity model under predict strength by 35% at age of 2 and 4 days and 33% at 7 days when compared with the results from the pullout tests.

Table 5.3: Strength Prediction Comparison between Maturity Model based on 14-Day and Pullout Test

Mixture	Concrete Element	Actual Days	Equivalent Age @ 23°C	Strength Predicted by 14-day Maturity Method (MPa)	Pullout Load (kN)	Strength Predicted by 14-day Pullout Correlation (MPa)
Control Mix	Block	2	3.43	15.99	17.20	18.00
		4	5.99	19.60	18.50	19.73
		7	8.38	21.44	21.50	23.84
	Slab	2	1.72	11.20	16.30	16.82
		4	2.88	14.78	19.0	20.40
		7	4.66	18.04	20.70	22.73
35 % FA-A Mix	Block	2	2.40	7.98	10.80	9.16
		4	4.60	11.72	11.10	9.51
		7	7.19	14.38	13.6-	12.49
50 % FA-A Mix	Block	2	2.42	13.48	16.60	14.85
		4	4.59	18.43	17.50	15.91
		7	7.19	20.93	18.20	16.75
	Slab	2	1.58	10.39	11.80	9.50
		4	3.17	15.55	14.80	12.78
		7	5.02	19.04	17.10	15.43
35 % FA-C Mix	Block	2	3.42	17.73	20.40	27.47
		4	6.02	22.97	23.0	35.44
		7	9.21	26.54	24.30	39.82

Table 5.4: Percent Difference between in predicted strength between 14-day pullout and 14-day maturity method

Mixture	Concrete Element	Actual Days	Equivalent Age @ 23°C	14-day Maturity Method (%)
Control Mix	Block	2	3.43	-11.67
		4	5.99	-0.67
		7	8.38	-10.07
	Slab	2	1.72	-33.40
		4	2.88	-27.57
		7	4.66	-20.63
35 % FA-A Mix	Block	2	2.40	-12.90
		4	4.60	23.21
		7	7.19	15.16
50 % FA-A Mix	Block	2	2.42	-9.23
		4	4.59	15.85
		7	7.19	24.97
	Slab	2	1.58	9.40
		4	3.17	21.65
		7	5.02	23.40
35 % FA-C Mix	Block	2	3.42	-35.45
		4	6.02	-35.17
		7	9.21	-33.36

In match curing, the temperature profile inside the structure is recorded and replicated on testing cylinders. Thus, the cylinders experience the same rate of strength gain as the concrete in the structure. This makes the match cured strength predictions accurate for the in-place compressive strength determination. Hence, it is also important to compare the 14-day based maturity models with the match cured strength, as well as against existing methods like the field cured strength and the 28-day maturity models. Table 5.5 provides this comparison. Table 5.5 also provides the comparison of setting time approach with other methods.

As can be seen from Table 5.5, the field cured strength method predicts a strength of 8.60 MPa, 13.90 MPa and 18.0 MPa for the control mix block at ages of 2, 4 and 7 days respectively. The match cured strength at these ages is 19.40 MPa, 23.70 MPa and 26.60 MPa respectively. This translates to an under prediction of 55.00%, 41.40% and 32.00% at ages of 2, 4 and 7 days respectively. Similar effects are observed in the case of concrete slabs with the control and the 35% FA-A mix, as well as the remaining mixtures. Thus, the field cured method provides consistently lower strength predictions.

For the control mix, there is a small difference between the values predicted from the 14-day and the 28-day based maturity models for all the ages, as it can be seen in Table 5.5. For example, in the block with the control mix at the age of 2 days, the 14-day maturity model predicts a strength of 15.99 MPa while the 28-day maturity model predicts a strength of 16.30 MPa. Even in the case of slab, at the age of 2 days, the 14-day maturity model predicts a strength of 11.20 MPa while the 28-day maturity model predicts a strength of 11.10 MPa. Thus, these two maturity modeling methods provide similar strength predictions at early ages. However, at the age of 28-days for the concrete block, the 28-day based maturity model predict the strength of 29.73 MPa while the14-day maturity model predicts a 26.40 MPa strength. The actual strength of concrete at 28 days is 29.84 MPa as determined from the match cured strength.

Differences in predictions, were examined on the 14-day and 28-day maturity model and the results are provided in Tables 5.3 and 5.4. This predictions may be positive or negative depending on whether the model over-predicts or under-predicts the in-place strength at a specific age in relation to the match cure strength. In this way, the differences, reported here in as “errors” across all testing ages are computed and an “average error” for the model is determined. This analysis reveals that the 28-day maturity model provides closer strength predictions to the match cured strength for the control mix. . Both the 14-day maturity and 28-day maturity models under predict the in place compressive strength when compared with the match cured strength.

For the 35% FA-A block, the results are similar to the one observed for the control mix. There is a small difference in predicted values from the 14-day maturity and the 28-day maturity methods For example, as it can be seen from Table 5.5, at the age of 4 days, the 14-day based maturity model predict a strength of 11.72 MPa while the 28-day model predicts a strength of 11.20 MPa. The match cure strength at this age was 16.90 MPa. These analyses are provided in Tables 5.7-5.12. From the “error” analysis, it was observed that the 28-day model under-predicts the 2 day strength by 45.00% while the 14-day model under-predicts by 40.00%. The 14-day maturity model offer some improvement over the existing 28-day maturity model at all ages by reducing the strength under-prediction at each testing age

In the case of 50% FA-A mix, the 14-day model provide better estimates of the in place strength than the 28-day based maturity model. For example, at the age of 4 days for the concrete block, the 14-day based maturity model predicts the strength of 18.43 MPa while for the 28-day model is 16.70 MPa. The match cure strength at this age is 19.50 MPa. Even for the slab, the 14-day model predicts an in-place strength of 15.54 MPa while the 28-day model predict a strength of 14.00 MPa. The strength at this age is 15.60 MPa. The 14-day models consistently predict higher values of in place strength at each testing age than 28-day models thereby reducing the degree of under-prediction. .

In the case of the 35% FA-C mix, the 28-day model consistently predicts higher values of the in-place strength than the 14-day model. For example at the age of 2, 4 and 7 days the 28-day model predicts strengths of 20.70 MPa, 25.80 MPa and 29.00 MPa respectively while the 14-day model predict strengths of 17.70 MPa, 22.97 and 26.53. The match cure strength at these ages are 23.60 MPa, 30.40 MPa and 34.20 MPa respectively. Such results perhaps imply that the 14-day model is not able to capture the mass concrete effect in large structures as effectively as the 28-day model has. Also, from table 5.5

it is evident that the results of setting time approach agree with the results from 14-day maturity approach for all the concrete mixtures.

Table 5.5: Strength Comparison by Different Methods

Mixture	Concrete Element	Actual Days	Match Cured Strength (MPa)	Strength Predicted by 14-day Maturity Method (MPa)	Field Cured Strength (MPa)	Strength Predicted by Pullout Correlation (MPa)	Strength Predicted by 28-Day Maturity Method (MPa)	Strength Predicted by 14-Day Setting Time method (MPa)
Control Mix	Block	2	19.40	15.99	8.60	18.00	16.30	16.44
		4	23.70	19.60	13.90	19.73	20.40	19.91
		7	26.60	21.44	18.00	23.84	22.70	21.61
	Slab	2	19.50	11.20	11.80	16.82	11.10	11.22
		4	25.00	14.77	15.80	20.40	14.20	14.68
		7	29.60	18.04	22.30	22.73	17.60	17.91
35% FA-A Mix	Block	2	12.40	7.98	9.10	9.16	9.10	7.48
		4	16.90	11.72	9.50	9.51	11.20	11.25
		7	19.20	14.38	12.40	12.49	14.00	14.21
50% FA-A Mix	Block	2	14.90	13.48	14.80	14.85	12.10	13.17
		4	19.50	18.43	15.90	15.91	16.70	18.14
		7	22.40	20.93	16.80	16.75	19.90	20.73
	Slab	2	10.30	10.39	9.30	9.50	10.00	10.24
		4	15.60	15.55	12.70	12.78	14.00	15.37
		7	17.60	19.04	15.40	15.43	17.70	18.91
35% FA-C Mix	Block	2	23.60	17.73	22.90	27.47	20.70	18.73
		4	30.40	22.97	26.60	35.44	25.80	23.75
		7	34.20	26.54	28.40	39.82	29.00	27.04

Table 5.6: Percent differences between match cured and other methods

Mixture	Concrete Element	Actual Days	14- Day Maturity Method (%)	Field Cure Strength (%)	Pullout Correlation (%)	28-Day Maturity Method (%)	14-Day Setting Time Method (%)
Control Mix	Block	2	-17.60	-55.70	-7.20	-16.00	-15.26
		4	-17.31	-41.40	-16.80	-13.90	-15.99
		7	-19.40	-32.30	-10.40	-14.70	-18.76
	Slab	2	-42.60	-39.50	-13.74	-43.10	-42.46
		4	-40.90	-36.80	-18.40	-43.20	-41.28
		7	-39.10	-24.70	-23.20	-40.50	-39.49
35% FA-A Mix	Block	2	-35.70	-26.60	-26.10	-26.60	-39.68
		4	-30.70	-43.80	-43.70	-33.70	-33.42
		7	-25.10	-35.40	-35.00	-27.10	-25.99
50% FA-A Mix	Block	2	-9.50	-0.67	-0.34	-18.80	-11.61
		4	-5.50	-18.50	-18.40	-14.40	-6.97
		7	-6.60	-25.00	-25.20	-11.16	-7.46
	Slab	2	0.90	-9.70	-7.80	-2.90	-0.58
		4	-0.34	-18.6	-18.10	-10.30	-1.47
		7	8.20	-12.50	-12.30	0.60	7.44
35% FA-C Mix	Block	2	-24.90	-2.96	16.40	-12.30	-20.64
		4	-24.40	-12.50	16.60	-15.10	-21.88
		7	-22.40	-17.00	16.40	-15.20	-20.91

Figure 5.1 presents strength predictions for the concrete block with the control mix along with comparing results from field cured, match cured, pullout strength and 28-day maturity methods. As discussed

previously, the field cured method under-predicts concrete strength. There is a small difference between the predicted values from the14-day maturity and 28-day maturity models. However, the 28-day maturity prediction model provides closer predictions to the 28 day strength of concrete from the match cure approach.

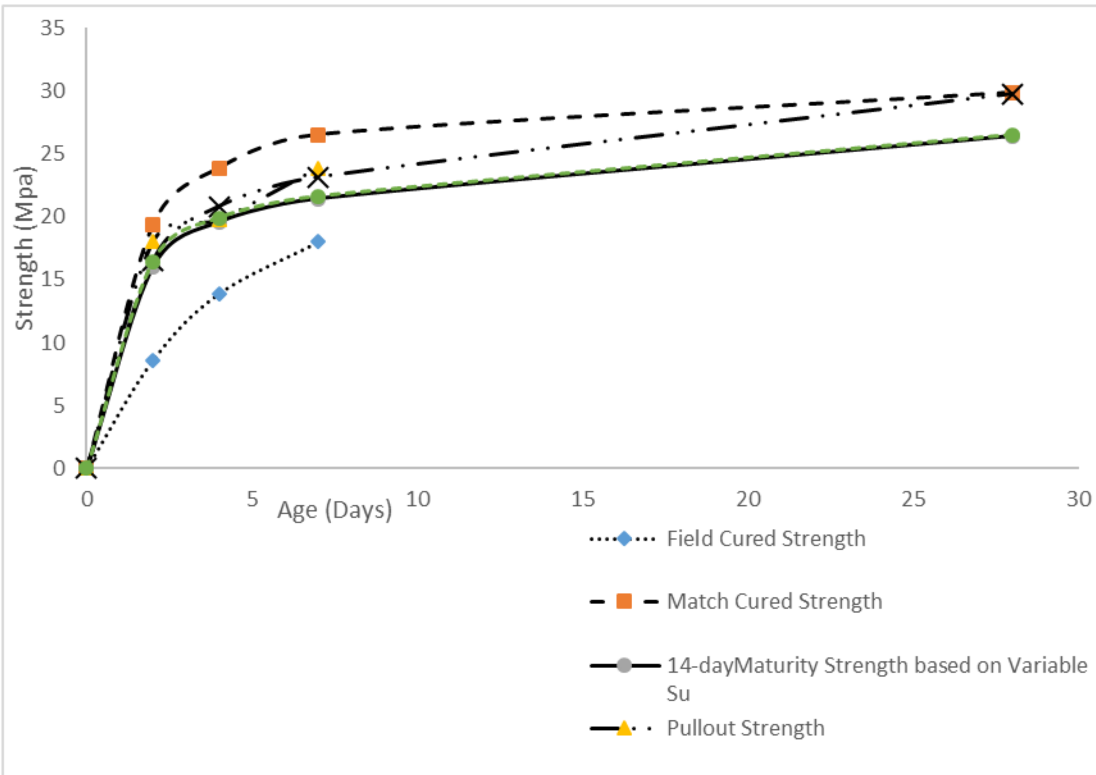

Figure 5.1: Strength Comparison for Control Mix Block by different methods

Note: 28-day match cured strength predicted based on section 4.2.1 procedure

Figure 5.2 presents the strength prediction of concrete slab with the control mix along with comparing results from the field cured, match cured, pullout strength and 14 and 28-day maturity methods. Similar effects as in the case of the control mix concrete block are observed as well.

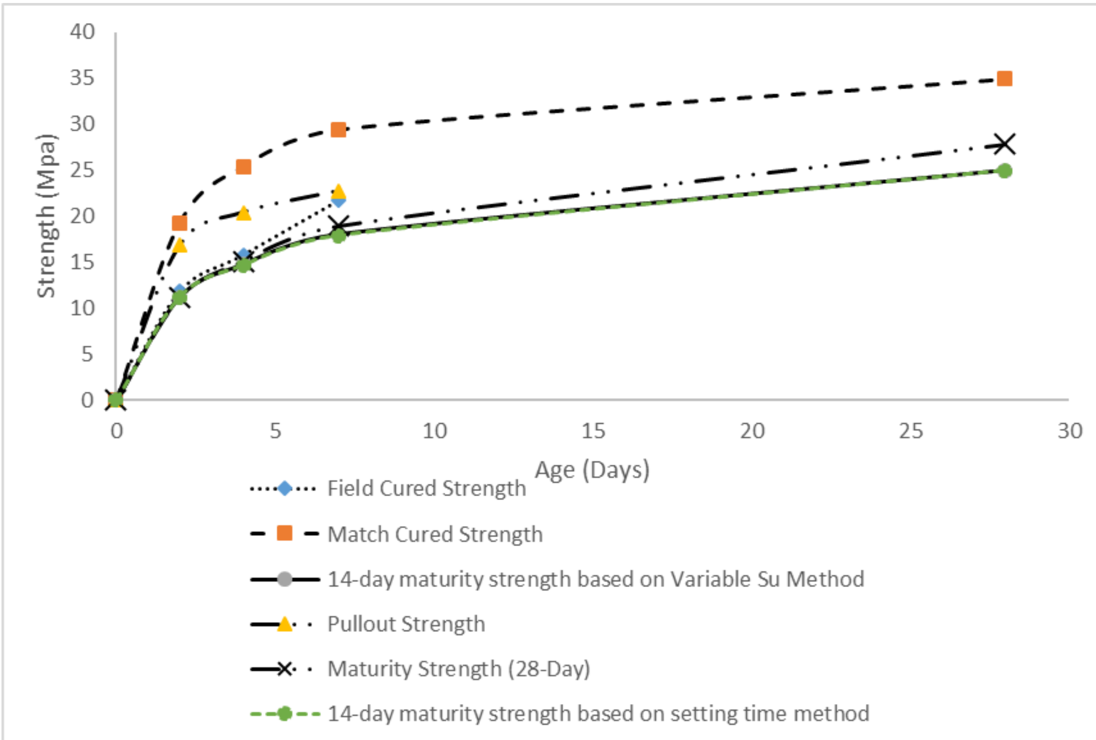

Figure 5.2: Strength Comparison for Control Mix Slab by different methods

Note: 28-day match cured strength predicted based on section 4.2.1 procedure

Figure 5.3 presents the strength prediction of the concrete block with the 35% FA-A mix along with comparing results from the field cured, match cured, pullout strength and the 14-day and 28-day maturity methods. From Figure 5.3, it may appear as if the 28-day model predict better the in-place match cure strength. However, as explained earlier, the error analysis revealed that overall the 14-day model provides overall a lower difference in predicted values from match cure data than the 28-day model.

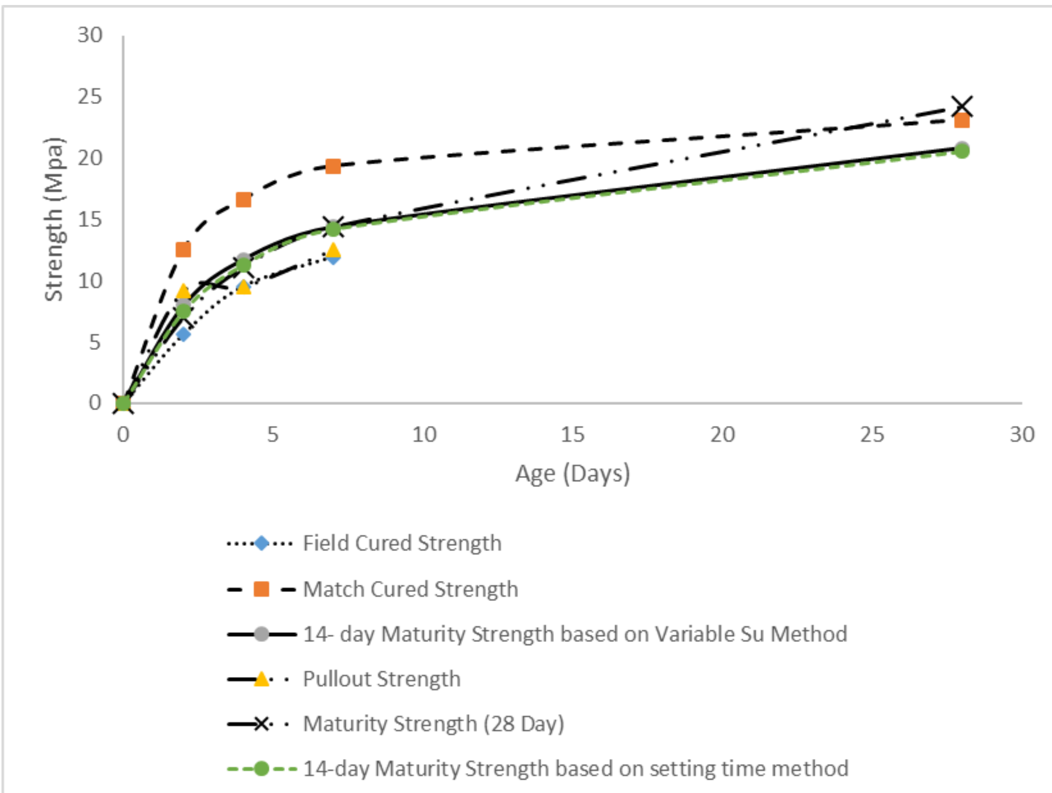

Figure 5.3: Strength Comparison for 35% FA-A Block by different methods

Note: 28-day match cured strength predicted based on section 4.2.1 procedure

Figure 5.4 presents the strength prediction for the concrete block of the 50% FA-A mix along with comparing the results from the field cured, match cured, pullout strength, and 14 and 28-day maturity methods. At each testing age, the 14-day model predicts more accurate the in-place strength which was also observed from the data in Table 5.5.

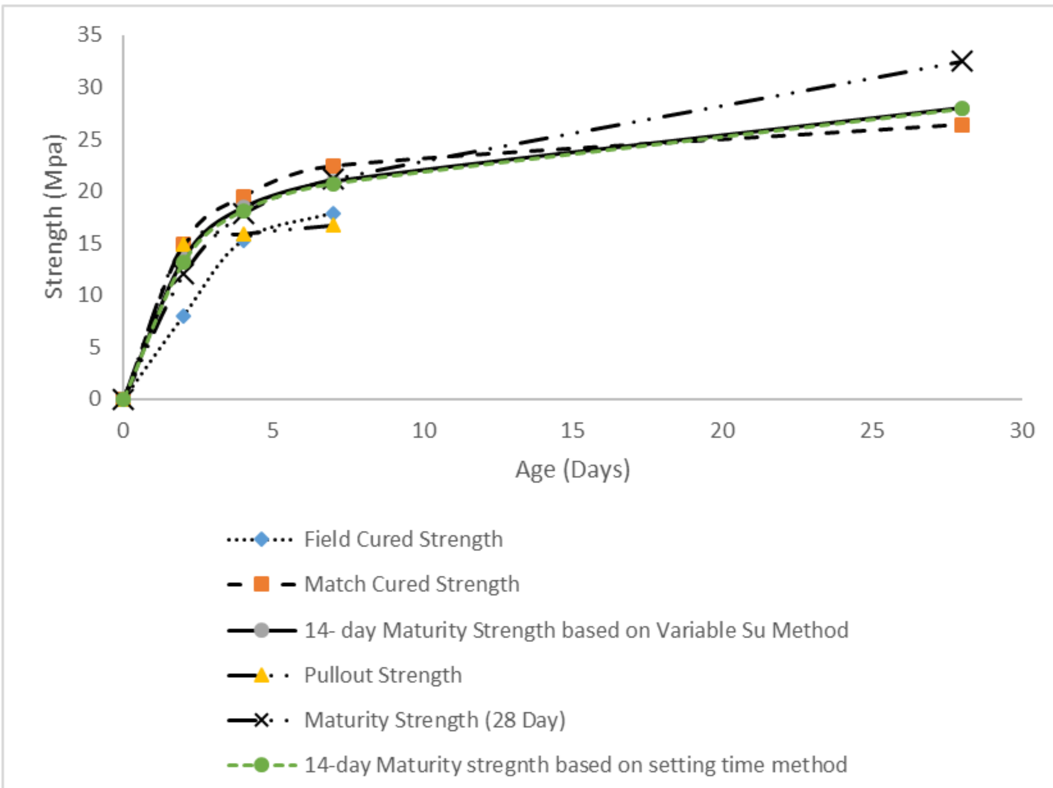

Figure 5.4: Strength Comparison for 50% FA-A Block by different methods

Note: 28-day match cured strength predicted based on section 4.2.1 procedure

Figure 5.5 presents the strength prediction of the concrete slab with of the 50% FA-A mix. The trend is similar to that observed in the case of the 50% FA-A block. At each testing age, the 14-day model predicts as well better the in-place strength, as it was observed from Table 5.5 as well.

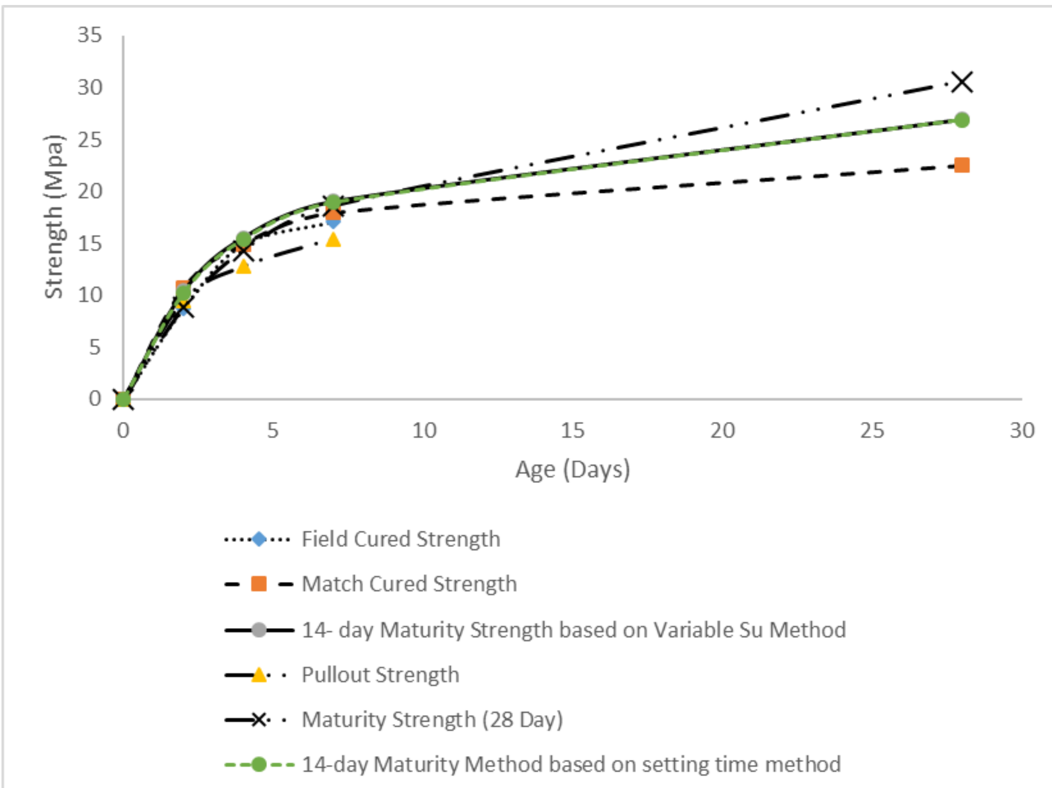

Figure 5.5: Strength Comparison for 50% FA-A Slab by different methods

Note: 28-day match cured strength predicted based on section 4.2.1 procedure

Figure 5.6 presents the strength prediction of the concrete block with the 35% FA-C mix as discussed earlier, in this case the 28-day maturity model provide closer in-place compressive strength than the 14-day maturity model.

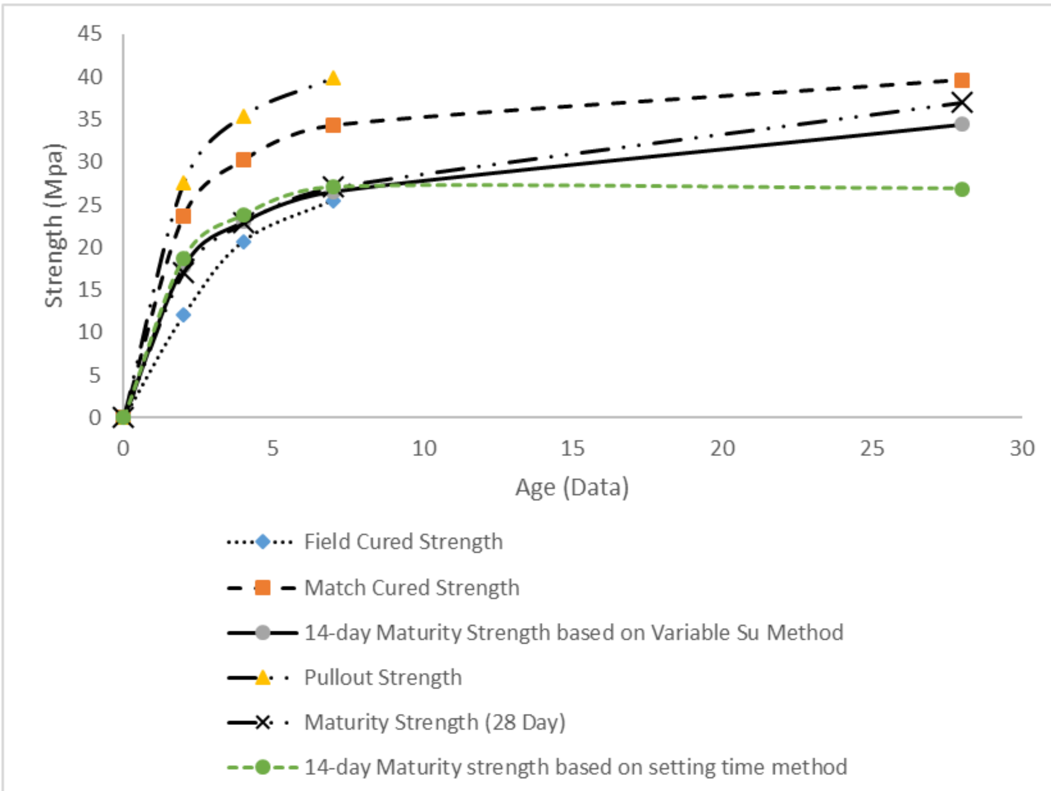

Figure 5.6: Strength Comparison for 35% FA-C Block by different methods

Note: 28-day match cured strength predicted using section 4.2.1 procedure

The “error” analysis described previously for all the mixtures are provided in Tables 5.7 to 5.12.

Table 5.7: Error Analysis for the Control Mix Block

Control Mix Block		Variable Su Approach	
Days	Match Cured Strength	% Error 14 day Model	% Error 28 day Model
0	0.00	0.00	0.00
2	19.33	-17.26	-14.65
4	23.85	-17.84	-12.71
7	26.51	-19.13	-12.74
28	29.84	-11.52	0.33

Table 5.8: Error Analysis for the Control Mix Slab

Control Mix Slab		Variable Su Approach	
Days	Match Cured Strength	% Error 14 day Model	% Error 28 day Model
0	0.00	0.00	0.00
2	19.29	-41.93	-42.33
4	25.40	-41.83	-40.58
7	29.39	-38.61	-35.61
28	34.86	-28.36	-20.31

Table 5.9: Error Analysis for the 35% FA-A Mix Block

35% FA-A Block		Variable Su Approach	
Days	Match Cured Strength	% Error 14 day Model	% Error 28 day Model
0	0.00	0.00	0.00
2	12.54	-36.38	-44.10
4	16.63	-29.55	-33.38
7	19.34	-25.62	-25.60
28	23.09	-9.77	4.88

Table 5.10: Error Analysis for the 50% FA-A Mix Block

50% FA-A Block		Variable Su Approach	
Days	Match Cured Strength	% Error 14 day Model	% Error 28 day Model
0	0.00	0.00	0.00
2	14.92	-9.64	-19.64
4	19.48	-5.39	-8.56
7	22.42	-6.64	-5.65
28	26.41	6.05	23.10

Table 5.11: Error Analysis for the 50% FA-A Mix Slab

50% FA-A Slab		Variable Su Approach	
Days	Match Cured Strength	% Error 14 day Model	% Error 28 day Model
0	0.00	0.00	0.00
2	10.69	-2.80	-17.65
4	14.90	4.35	-4.00
7	17.92	6.25	3.79
28	22.48	19.83	36.04

Table 5.12: Error Analysis for the 35% FA-C Mix Block

35 % FA-C Block		Variable Su Approach	
Days	Match Cured Strength	% Error 14 day Model	% Error 28 day Model
0	0.00	0.00	0.00
2	23.68	-25.12	-28.02
4	30.23	-24.00	-24.41
7	34.29	-22.62	-21.16
28	39.62	-13.18	-6.56

The sum of squares of prediction errors from the 14-day setting time method the 14-day maturity method and the 28 –day maturity method in relation to the match cure strength values are presented in table 5.13. Overall the 14-day setting time method and 14-day maturity method consistently provide lower sum of square errors in strength predictions than the 28-day maturity models for all the HVFA concrete mixtures.

Table 5.13: Sum of squares of prediction error by 14-day setting time method, 14-day maturity method & 28-day maturity method vs Match cured strength

Mix	Setting Time Method (14 Day)	Maturity Model (14 Day)	Maturity Model (28 Day)
Control Mix Block	13.67	14.94	11.17
Control Mix Slab	87.15	85.66	73.09
35% FA-A Block	21.68	18.91	42.74
50% FA-A Block	7.83	6.81	50.17
50% FA-A Slab	14.84	14.61	62.07
35% FA-C Block	31.84	38.35	43.95

Chapter 6 Summary, Conclusions and Recommendations

In this research, a new maturity strength prediction approach was examined based on the 14-day strength data. The ability of this approach to predict the in-place strength of concrete mixtures was evaluated against the traditional maturity modeling suggested by ASTM C1074 and results from in-place strength determination. To this effect, the following observations can be summarized for the different mixtures:

1) The 14-day Pullout force vs compressive strength correlations were developed in this research. The results reveal that the 14-day pullout correlations offer small improvements in estimating the in-place compressive strength for the conventional concrete (control) mix, the concrete mix with 35% of type F fly ash and the concrete mix with 50% of type F fly ash. In case of the concrete mix with 35% of type C fly ash, it was found that the 28-day pullout correlations provide better estimates of the in-place compressive strengths.

2) The comparisons of the 14-day maturity models with the14-day pullout correlations reveal that the 14-day maturity models

consistently under-predict the in-place compressive strength of the conventional concrete (control) mix and the concrete mix with 35% of type C fly ash. For the concrete mix with 35% of type F fly ash and the concrete mix with 50% of type F fly ash, 14-day maturity model consistently predict higher values of the in-place compressive strength than the 14-day pullout correlations.

3) The strength of the concrete mixtures at each testing day is revealed by the match curing strength and these values indicate that the 14-day maturity models provide closer estimates to in-place strength than the 14-day pullout correlations in the case of concrete mixtures with 35% and 50% of type F fly ash. The 14-day maturity models provide more accurate estimates of in-place strength for these mixtures than the 14-day pullout correlations.

4) The 14-day setting time approach for predicting in-place compressive strength was also explored in this research. For the conventional concrete mixtures and the mixtures with fly ash of type F, the predictions from setting time approach are identical to the predictions from 14-day maturity models. Thus, the 14-day setting time approach

has shown promising results and can be used for developing prediction models for estimating in-place strength.

5) There is not a significant difference between the predicted values of early age strength of the control mix concrete (at ages 2, 4 and 7 days) using both the 14-day and the 28-day based maturity models. However, the 28-day maturity model predicts the later age strength (at 28 days) more accurately than the 14-day model. It is recommended to use the existing 28-day model for estimating the in-place compressive strength of the control mix concrete.

6) In the case of the 35% FA-A mix, the 14-day maturity model improves the estimation of the in-place compressive strength. The 28-day maturity model display greater variability in predicting the in-place strength of 35% FA-A mix.

7) The accelerated strength development in 50% FA-A mix due to mass effects is better captured by the 14-day maturity model than the 28-day model. The adopted research methodology has succeeded in reducing the variability in predicting the in-place strength.

8) The 28-day based maturity model predict the in-place strength of the 35% FA-C concrete more accurately than the 14-day maturity model.

On the basis of the analysis and results from various methods to estimate in-place compressive strength of concrete, the following conclusions were obtained from this research:

1) The 14-day pullout correlations have shown improvement over the 28-day pullout correlations in the case of conventional concrete (control) mixtures and the concrete mixture with higher percentages of type F fly ash. If pullout correlations are to be used for estimating in-place strength, it is recommended to use 14-day pullout correlations for the conventional concrete mixtures and for the concrete mixtures with higher percentages of type F fly ash.

2) The 14-day maturity models have shown an improvement in estimating in-place compressive strength of high volume fly ash concrete of type F.

3) The mass concrete effects on concrete hydration for flat structural elements, like concrete slabs, are minimal and do not provide contribution to a faster rate of hydration and earlier strength gain. Thus, the developed models were not as accurately predicting field strength as for the case of the concrete blocks. This was also observed from the match cure data.

4) The 14-day maturity models provide more accurate estimate of in-place compressive strength for the concrete mixture with higher percentages of type F fly ash than 14-day pullout correlations.

5) Field cured strength, one of the most commonly used method of in-place strength monitoring, provides the most conservative results. Relying solely on field cured test will delay scheduling of construction activities thereby increasing cost of construction.

6) The 14-day setting time method and the 14-day maturity method consistently provide lower sum of squares of errors in prediction of in-place strength for HVFA concrete of type F and type C.

7) The match curing approach replicates the actual temperature profile of the concrete structures into the testing cylinders. Thus, the testing cylinder and the concrete structure are cured at the same temperature. For this reason, the results from match curing are more accurate than the other methods of in-place strength determination.

8) The process of developing maturity models by keeping the limiting strength constant was unable to represent the hydration of concrete mixture with different types and amounts of fly ash.

9) The 14-day setting time approach was explored and presented in this research. The results are encouraging and this approach is suitable for developing maturity models.

10) To develop more accurate prediction models, it is imperative to capture the activation energy of different mixtures more accurately. Traditional methods of estimating activation energy have yielded variable results as seen in this research. Further investigations is needed to explore more accurate methods for determination of activation energy.

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