Effect of Temperature-Time History on Concrete Strength in Mass Concrete Structures

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ABSTRACT

Concrete maturity method has been used as a non-destructive method to estimate in-place strength development of concrete structures. Many state highway agencies have adopted the maturity method to obtain better quality control while monitoring concrete strength development in real time. The results of this study provide useful information to examine the feasibility and accuracy of the maturity method used in the estimation of concrete strength in large structures.

INTRODUCTION

- The strength of properly batched, placed and vibrated concrete does not depend only on the curing time, but also on the temperature-time history. This concept is known in the concrete industry as maturity concept.
- According to the maturity concept, an empirical relationship can be established between temperature-time history and strength development of the concrete in order to predict strength of in-place concrete during the curing period.
- In this study "Equivalent Age" approach was used to establish maturity-strength relationship. The actual age of the concrete was converted to its equivalent age (t_e) at a specified temperature (T_s) following "Arrhenius Equation":

$$t_e = \sum e^{-Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \Delta t$$

RESEARCH METHODOLOGY

- Six-ft concrete cube blocks were constructed at different locations in West Virginia, using four different concrete mixtures from local ready-mix plants (Table 1).
- Each cube was instrumented with temperature loggers attached on a rebar cage and temperature-time history was recorded for 56 days.
- 6x12 in. cylinders were collected and maturity-strength relationships were established using the linear hyperbolic equation suggested by ASTM C1074:

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

where "S" is the limiting strength, "S_u" is the ultimate strength and "k" is the rate constant.

- Activation energy values for the concrete mixtures were determined in the laboratory following ASTM C1074.
- Core samples were taken from the hardened concrete cube blocks at 4, 28 and 56 days, and the measured compressive strengths from the core samples were compared to the predicted in-place compressive strengths.
- The applicability of maturity method in predicting the strength of in-place concrete that has high early temperature was investigated using WVDOH approved Class B and Class B Modified concrete mixtures.

Table 1- One yd^3 Theoretical Mix Design

Item	D1	D9	D5	D6
	Class B Fly-Ash	Class B	Class B GGBFS	Class B Modified
Cement (TYPE I/II), lbs	470	564	423	658
Fly-Ash (TYPE F). lbs	75	-	-	-
GGBFS (Grade 100), lbs	-	-	141	-
Water, lbs	245	262	276	260
Coarse Aggregate (#57), lbs	1775	1723	1815	1750
Fine Aggregate, lbs	1255	1299	1225	1111
Target Air Content, %	7.0	7.0	7.0	7.0
w/cm	0.45	0.45	0.49	0.40

6-FT CUBE CONSTRUCTION

Six-ft concrete cubes were constructed at four different WVDOH Districts located in Charleston (D1), Lewisburg (D9), Martinsburg (D5), and Wheeling (D6), pouring approximately nine cubic-yards of concrete in each cube provided by local ready-mix concrete plants. Each cube was instrumented with temperature loggers attached on a rebar cage and temperature-time history was recorded as shown in Figure 3.

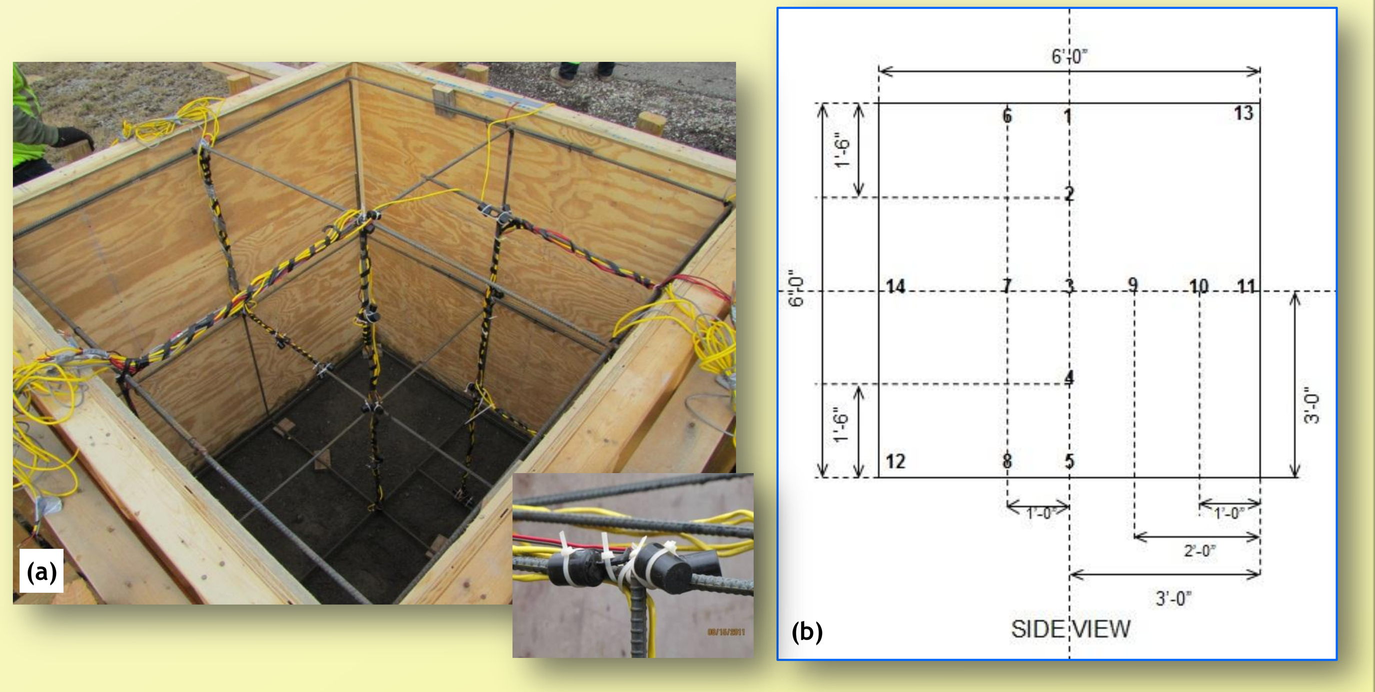

Figure 1- Cube construction (a) Instrumentation (b) Schematic of the sensor locations.

Figure 2- Cube construction, concrete pouring, placement and making concrete cylinders.

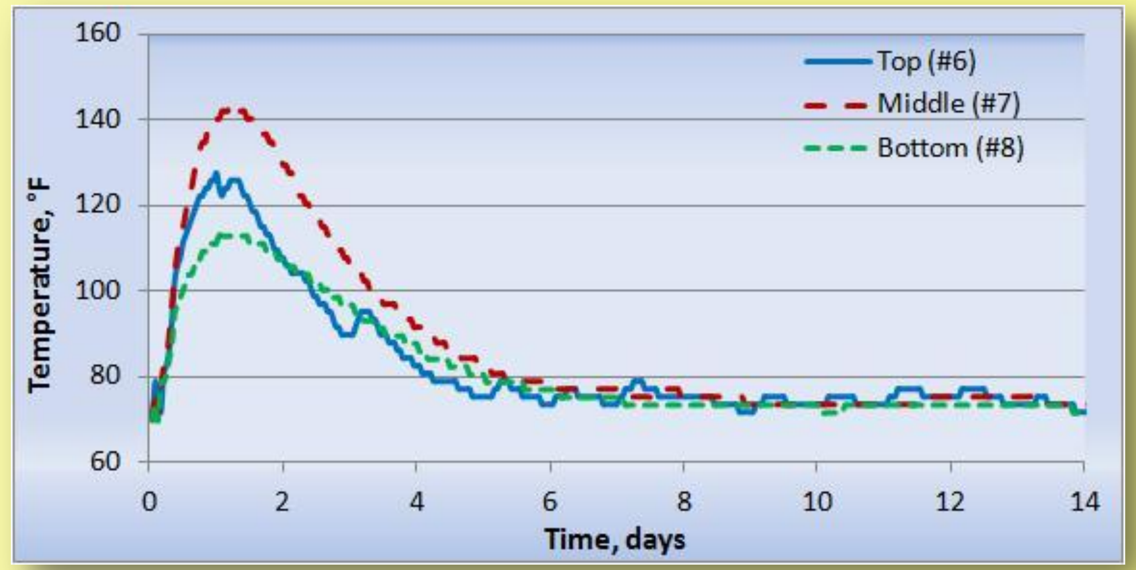

Figure 3- Measured concrete temperature-time history from D5 Cube.

MATURITY METHOD

Maturity-Strength Relationship

In order to establish the maturity-strength relationship of each mix, a calibration curve was prepared from strengths of the laboratory cured cylinders with recorded temperature-time history. The calibration curve that represents the strength gain of the concrete was modeled using the linear hyperbolic equation.

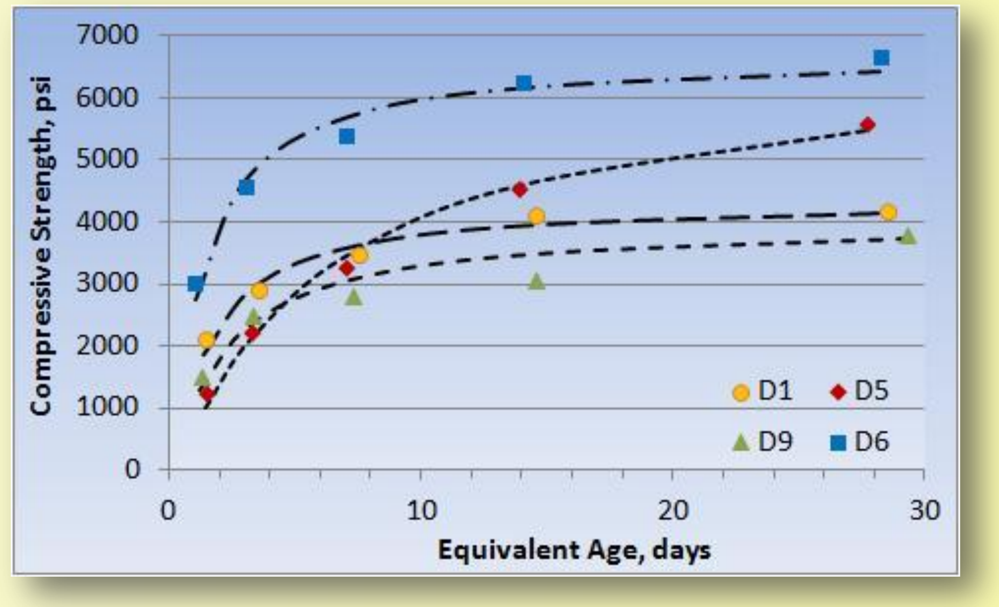

Figure 4- Concrete compressive strength calibration curve, strength vs equivalent age.

Determination of Activation Energy

The apparent activation energy values of 45,900 J/mol and 44,750 J/mol for Class B Fly-Ash (D1) and Class B GGBFS (D5) concrete mixtures, respectively, were determined using 2-inch mortar cubes cured at three different temperatures: 104°F, 73°F and 50°F. These values were calculated based on the Arrhenius function which was used to explain the temperature dependence of the rate constant, "k" from the hyperbolic equation.

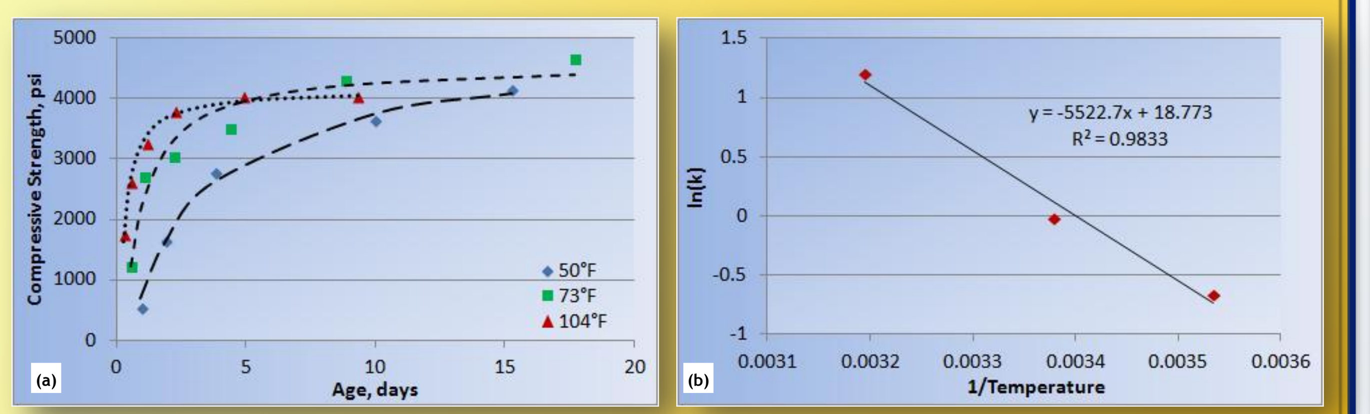

Figure 5- D1 Class B Fly-Ash (a) Mortar strength (b) Activation Energy.

CORE STRENGTH

6-ft Core

A total of six 4x8 inch cylinder specimens were prepared from the cores along the 6-ft length (Figure 7) and the compressive strength results were obtained at 4, 28 and 56 days from each core (Table 2).

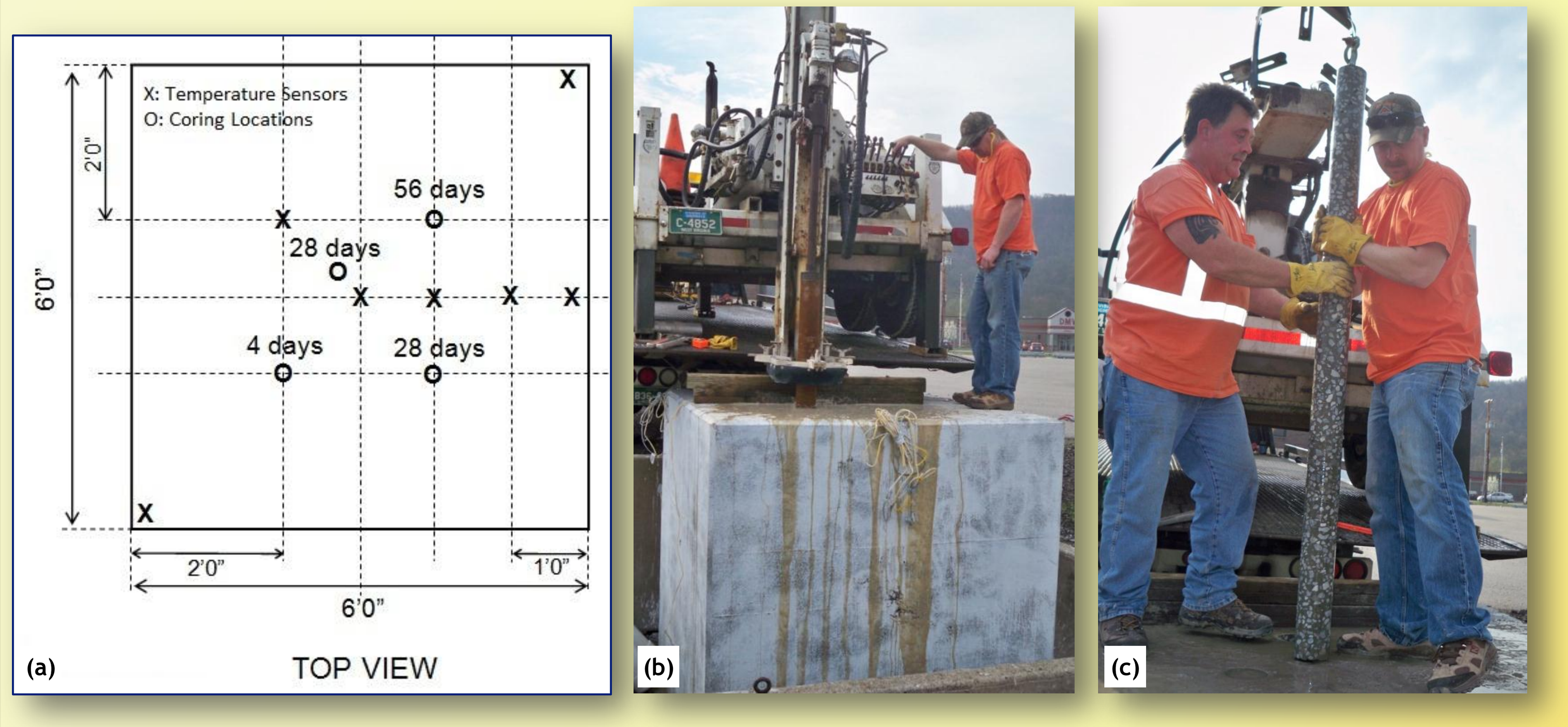

Figure 6- Coring (a) Schematic of the coring locations (b) Coring machine (c) 6-ft core extraction.

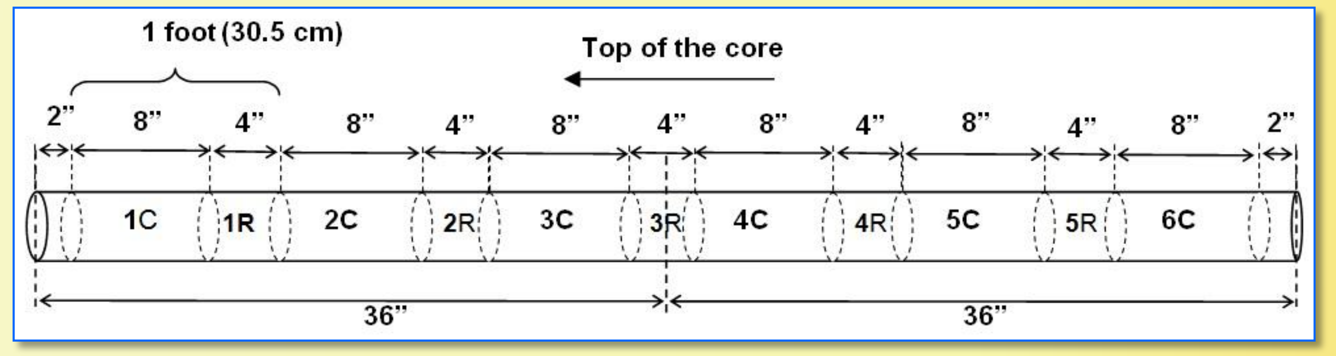

Figure 7-Core specimen cut locations and designations.

Table 2- Compressive Strength from the 6-ft Core at 28-day and 56-day

		1C	2C	3C	4C	5C	6C
Depth from the surface, inches		2"-10"	14"-22"	26"-34"	38"-46"	50"-58"	62"-70"
D1 CUBE	28 Days (center)	4,750	5,640	5,600	4,950	6,460	6,540
	29 Days (corner)	4,370	5,600	5,640	5,490	6,070	5,900
	56 Days	4,690	6,130	5,920	5,820	6,370	6,410
D5 CUBE	28 Days (center)	4,460	6,080	5,820	5,570	5,630	6,960
	28 Days (corner)	4,510	4,800	5,150	6,040	5,700	6,590
	76 Days	4,180	5,750	5,580	5,310	6,090	7,430
D9 CUBE	28 Days (center)	2,960	2,670	2,520	3,710	3,630	4,120
	28 Days (corner)	3,150	2,630	2,510	3,790	3,740	4,210
	56 Days	3,350	2,730	2,640	4,000	3,840	4,330
D6 CUBE	28 Days (center)	6,010	6,440	5,150	6,490	6,210	6,230
	28 Days (corner)	5,730	6,160	5,450	5,980	6,090	6,400
	56 Days	5,390	6,530	6,160	6,590	6,630	6,440

IN-PLACE CONCRETE STRENGTH ESTIMATION

In order to estimate the in-place concrete strength, temperature sensors were installed at 2", 36" and 70" from the cube top surface, corresponding to top section (#6), mid-section (#7) and bottom section (#8). The locations were selected to be representative of the temperatures at the locations of coring due to symmetry. In-place concrete strengths were estimated using strength-equivalent age calibration curves for each concrete mixture.

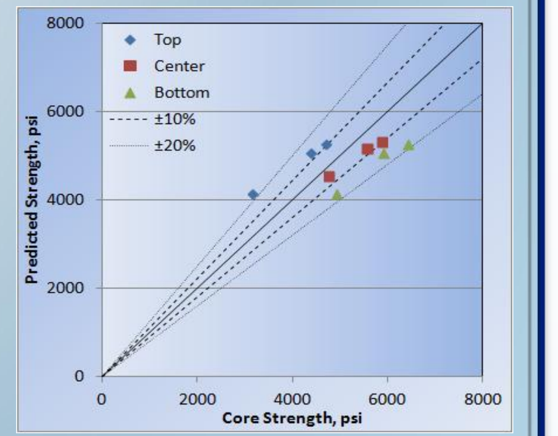

Figure 8- Predicted in-place concrete strength vs. average core strength at 4,28, and 56 days for D1 Cube

Table 3- In-place Concrete Strength Prediction Compared with the 4-day Core Strength from Four 6-ft Cubes

	Equivalent age, days	Predicted Strength, psi	Core Strength, psi	Equivalent age, days	Predicted Strength, Psi	Core Strength, psi
	D1			D5		
Top	14.1	3,920	3,160	11.7	4,310	3,880
Center	21.2	4,060	4,760	18.2	4,970	4,830
Bottom	13.9	3,920	4,930	10.5	4,130	5,300
	D9			D6		
Top	17.3	3,370	2,420	20.3	6,330	4,460
Center	31.1	3,500	3,620	24.5	6,400	3,710
Bottom	19.0	3,400	4,010	10.0	5,970	5,250

CONCLUSIONS

- The hyperbolic strength-age relationship was used to model strength development at different temperatures. Activation energy values for concrete mixtures including supplementary cementitious materials were successfully determined following ASTM C1074.
- Test results show that the in-place concrete core strengths of the six-ft cube close to the concrete top surface were overly estimated by the maturity method. For D1, D5 and D9 cubes, concrete strength at the mid-section were close to the predicted strength.
- Effect of variable temperature curing in large structures cannot be accurately predicted by the current maturity calculation using linear hyperbolic equation.
- Further study is needed to modify the maturity calculation for its application in mass concrete with large temperature variations.
- The error in estimating in-place concrete strength is highly dependent on the quality control issues on-site, including in-situ water-cementitious ratio, air content, vibration/consolidation, and finishing.

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REFERENCE

Yikici, T. A. and Chen H. L., "Effect of Temperature-Time History on Concrete Strength in Mass Concrete Structures", TRB 92nd Annual Meeting, January 2013, Washington, D.C.