Maturity Method Evaluated for Various Cementitious Materials

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Abstract: The maturity method accounts for the effect of curing temperature on the strength development of well-cured and consolidated concrete. This paper describes an investigation of the accuracy of the maturity method to estimate the strength when different cementitious systems are used. Mortar cubes, made from Type I cement and various replacement levels of Class C fly ash, Class F fly ash, and ground-granulated blast-furnace slag, were cured at isothermal curing temperatures of 8, 23, and 40°C. The amount of long-term strength reduction, due to curing at high temperatures compared with curing at room temperature, is influenced by the type of cementitious system used in the concrete mixture. Based on the strength results of these mortar cubes and the procedure outlined in ASTM C 1074, datum temperature and activation energy values were determined for these cementitious systems. The ability of the equivalent age maturity method to accurately estimate the strength is significantly influenced by the composition of the cementitious material system.

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Introduction

It has been shown that the strength of well-cured and consolidated concrete is a function of its age and curing temperature history (Carino 1991). The maturity method is an approach that accounts for the combined effect of curing temperature and time on the development of concrete strength. This method requires that the temperature of the curing concrete be measured and recorded at regular intervals.

Fig. 1 presents the development of compressive strength for mortar specimens made from Type I cement cured at isothermal temperatures of 5, 12.5, 20, 35, and 50°C (Kjellsen and Detwiler 1993). It may be seen that the strength of the specimens cured at 50°C crosses over the strength of the specimens cured at 35°C after only 40 h. The long-term strength for specimens cured at 50°C was about 17% less than that of the specimens cured at 20°C. This behavior has been widely documented for the development of compressive strength (Carino 1991; Verbeck and Helmuth 1968). Carino (1991) termed this loss of strength due to curing at high temperatures the "crossover effect."

The possibility that high initial temperatures may cause decreased long-term strengths compared with a mixture cured at a low temperature cannot be accounted for in the formulation of the *classical* maturity method as defined in ASTM C 1074 (ASTM 2004). In recent years, there have been attempts to modify the classical maturity method to account for the crossover effect (Kjellsen and Detwiler 1993; Cervera et al. 1999). Other authors have come to a similar conclusion, and Byfors (1980) states that the "…following must consequently apply if a maturity function is to be able to take the influence of temperature on strength gain into consideration: the same strength must have been reached independently of the temperature at one and the same maturity (degree of hydration). This is not, however, always the case, curing at higher temperatures, 30–40°C, can entail losses in the final strength. Maturity functions cannot take effects of this type into consideration."

Some researchers have reported that the maturity method, for the purpose of providing strength estimates, will only provide accurate results up to a specific strength limit or maturity level. Byfors (1980) stated that since the maturity function cannot take into account the reduced ultimate strength due to higher curing temperatures, the maturity concept can only be applied at low maturities. Jonasson (1988) found that the maturity method worked satisfactorily up to about 50% of the 28-day strength reached after curing at an isothermal temperature of 20°C. Emborg (1989) also suggested a strength limitation of approximately 50% of the normal 28-day strength or about 48 h of equivalent age. Kjellsen and Detwiler (1993) stated that, ". . . at maturities beyond that corresponding to approximately 40% of the normal 28-day strength, the estimation may be erroneous." Pane and Hansen (2002) also stated that the ". . . classical maturity relation with the use of constant activation energy does not seem reliable for predicting the property development beyond $t_e = 72$ h (relative to curing time at 20°C)."

This paper describes an evaluation of the accuracy of the maturity method for estimating strength when different cementitious systems are used. The accuracy of the maturity method can be improved by using mixture-specific datum temperature or activation energy values. Datum temperature and activation energy values are recommended for different cementitious systems.

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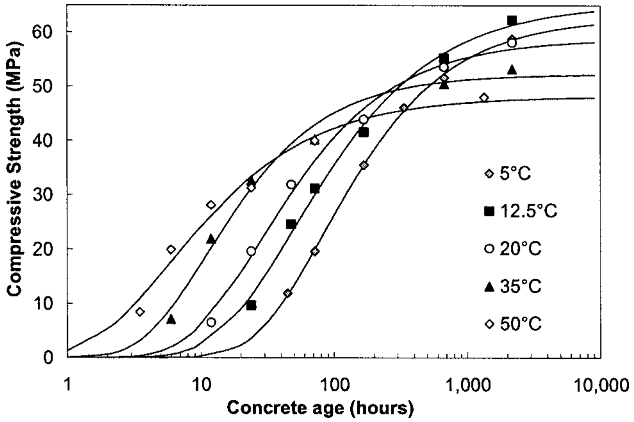

Fig. 1. Compressive strength results for mortar (adapted from Kjellsen and Detwiler 1993)

Research Significance

Currently, some construction projects use the maturity method to account for the effect of curing temperature on the strength development of concrete. In order to improve the accuracy of the maturity method, guidance on the selection of appropriate datum temperature and activation energy values is required when different cement types and supplementary cementing materials (SCMs) are used. Some researchers have suggested limitations on the strength range for which the maturity method will provide accurate results. This paper evaluates the accuracy of the equivalent age maturity method, and it is shown that poor strength estimates may be obtained for some cementitious material combinations, especially at high curing temperatures.

Background and Review of Maturity Theory

ASTM C 1074 (ASTM 2004) defines the maturity index as ". . . an indicator of maturity that is calculated from the temperature history of the cementitious mixture by using a maturity function." The same standard defines the maturity method as a technique for estimating concrete strength that is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of the maturity index. Classical maturity methods include both maturity functions recommended by ASTM C 1074: (1) the Nurse–Saul function, which is used to determine the time-temperature factor; and (2) the equivalent age formulation, from which an equivalent curing age relative to a reference curing temperature is calculated.

Definition of Classical Maturity Methods

Nurse (1949) showed that when relative strength development was plotted as a function of the product of time and temperature, the data for different concretes and curing cycles fell reasonably close to a single nonlinear curve. Saul (1951) introduced the term "maturity" and suggested that maturity should be calculated with respect to a datum temperature (T_0), which corresponds to the temperature at which no strength gain will occur. The maturity function shown in Eq. (1) was used by both Nurse and Saul, and is generally called the Nurse–Saul function for determination of maturity (ASTM 2004)

$$M = \sum_{0}^{t} (T_c - T_0) \cdot \Delta t \tag{1}$$

where M=maturity of the concrete (°C h); T_c=average concrete temperature during the time interval (°C); T_0=datum temperature (°C); and Δt=chronological time interval between temperature measurements (h). To use this maturity function, a datum temperature must be selected. Saul (1951) recommended a datum temperature of $-10.5°\text{C}$ and a value of $-10°\text{C}$ is commonly used today (Carino 1991). ASTM C 1074 recommends a datum temperature of $0°\text{C}$ for a Type I cement; however, no values are recommended for other cementitious systems.

Based on the Arrhenius rate theory for chemical reactions, Freiesleben Hansen and Pedersen (1977) developed the equivalent age maturity function shown in Eq. (2). The equivalent age maturity function converts the chronologic curing age of a concrete cured at any temperature, to an equivalent curing age (t_e) for a specimen cured at a reference temperature (T_r)

$$t_e(T_r) = \sum_{0}^{t} \exp\left[\frac{E}{R}\left(\frac{1}{273 + T_r} - \frac{1}{273 + T_c}\right)\right] \cdot \Delta t \tag{2}$$

where t_e=maturity in terms of equivalent age (h); E=activation energy (J/mol); R=universal gas constant (8.3144 J/mol/K); and T_r=reference temperature (°C). The reference temperature is generally assumed to be the standard laboratory curing temperature, which is usually either 20 or 23°C. The activation energy (E) defines the temperature sensitivity of a concrete mixture. The importance of the E value increases as the curing temperature becomes further removed from the reference temperature. Carino (1991) summarized a wide range of constant E values obtained by different researchers. These values ranged from 41,000 to 67,000 J/mol. Carino (1991) concluded that the value of the activation energy depends on the cement chemistry, cement fineness, type and quantity of cement, and admixtures used in the mixture. Most of the E values summarized by Carino were constant and independent of the concrete temperature.

Freiesleben Hansen and Pedersen (1977) proposed the activation energy formulation shown in Eq. (3), which is a function of the concrete temperature (T_c). This activation energy formulation was developed by calibrating the equivalent age maturity method to produce the best-fit results of compressive strengths ($t_e < 100$ h) performed at isothermal curing temperatures ranging between -10 and $80°\text{C}$

$$\text{for } T_c \geqslant 20\,°\text{C}$$

$$E(T_c) = 33{,}500 \text{ J/mol}$$

$$\text{for } T_c < 20\,°\text{C}$$

$$E(T_c) = 33{,}500 + 1{,}470(20 - T_c) \text{ J/mol} \tag{3}$$

When a Type I cement with no admixtures is used, ASTM C 1074 (ASTM 2004) recommends a constant E in the range of 40,000–45,000 J/mol for strength estimating applications. ASTM C 1074 provides no guidelines for the selection of an appropriate E when any other cement type or admixtures are used. ASTM C 1074 provides a test procedure to determine a mixture-specific datum temperature or activation energy value based on the development of mortar compressive strengths at three isothermal curing temperatures.

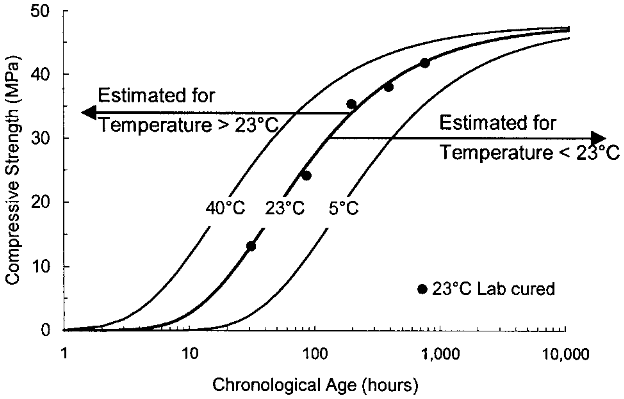

Fig. 2. Effect of classical maturity method

Carino and Tank (1992) studied the strength development of concrete and mortar specimens made with different cementitious systems and water-to-cementitious materials ratios (w/cm). They concluded that the E for a concrete mixture could be obtained from the strength-gain data of mortar cubes. Based on concrete specimens with a $w/\mathrm{cm}=0.45$, Carino and Tank (1992) obtained E values of 63,000 J/mol for Type I cement; 51,100 J/mol for Type II cement; and 43,000 J/mol for Type III cement. They also found that the addition of SCMs and chemical admixtures altered the E for a particular cement.

Key to understanding the concept behind the *classical* maturity methods is realization that temperature only effects the time to reach a given strength. Fig. 2 contains strength test data for cylinders moist cured at an isothermal temperature of 23°C. The best-fit strength-maturity relationship defined at a reference temperature of 23°C is shown to provide a good fit of the data. Based on this strength-maturity relationship, the maturity method (ASTM 2004) was used to estimate the strength at isothermal curing temperatures of 5 and 40°C, and these curves are shown in Fig. 2. From Fig. 2 it is evident that the maturity method is only able to translate the estimated strength development with respect to time, and the strengths estimated at different curing temperatures all approach the same ultimate strength. The classical maturity method thus inherently assumes that the long-term strength level of the concrete mixture is unaffected by the curing temperature.

Strength-Maturity Relationships

Many equations have been published to characterize the strength-age (and strength-maturity) relationship. The exponential and hyperbolic strength-age relationships are often used, and both are recommended by ASTM C 1074. The exponential strength-age formulation, shown in Eq. (4), was found to effectively characterize the *s*-shaped development of the compressive strength (Carino 1991; Freiesleben Hansen and Pedersen 1985)

Exponential

$$S(t) = S_u \cdot \exp\left(-\left[\frac{\tau}{t}\right]^{\beta}\right) \tag{4}$$

where $S(t)$=compressive strength at time t (MPa); S_u=ultimate compressive strength (MPa); t=chronological age (h); β=shape constant; and τ=time constant (h). The hyperbolic strength-age equation, shown in Eq. (5), was also found to effectively characterize the compressive strength development (Carino 1991). Both relationships approach an asymptotic strength, S_u, which corresponds to the best-fit ultimate concrete strength. The Annex of ASTM C 1074 uses the hyperbolic function to determine the datum temperature and the E for a specific mixture

Hyperbolic

$$S(t) = S_u \cdot \frac{K \cdot (t - t_0)}{1 + K \cdot (t - t_0)} \tag{5}$$

where t_0=age when strength development begins (h); and K=rate constant for the hyperbolic strength-age relationship (h^{-1}).

Experimental Work

Tank and Carino (1991) evaluated the isothermal strength development of concrete and mortar specimens made with different cementitious systems. They concluded that the activation energy results obtained from both concrete and mortar specimens are comparable. Based on these results, the Annex of ASTM C 1074 provides an experimental procedure to determine datum temperature and activation energy values for a concrete mixture based on the compressive strength development of mortar cubes cured at three different isothermal curing temperatures. This approach was used for this study, and the experimental procedures and materials tested will be discussed in the remainder of this section.

Datum Temperature and Activation Energy Testing Procedure

The ASTM C 1074 method was used to determine the strength gain of mortar specimens cured at different isothermal temperatures. Mortar cubes, $51 \times 51 \times 51$ mm in dimension, were made in accordance with ASTM C 109, "Standard test method for compressive strength of hydraulic cement mortar." As recommended by ASTM C 1074, an equivalent mortar was obtained by proportioning the mortar to have a fine aggregate-to-cement ratio equal to the coarse aggregate-to-cement ratio of the concrete. The mortars were also proportioned to have equal w/cm and amounts of admixtures as the corresponding concrete mixtures.

The mortar cubes were cured at isothermal temperatures of 8, 23, and 40°C by keeping them immersed in controlled-temperature water baths saturated with calcium hydroxide. All the raw materials were stored at the curing temperature before mixing. When the cubes were removed from the baths to be tested in compression, drying and cooling of them were prevented by transporting the cubes in containers filled with water obtained from that particular curing bath.

Eighteen cubes were made for each isothermal curing temperature. Sets of three cubes were tested at six different ages. ASTM C 1074 recommends that the first set of cubes be tested at approximately twice the time of final setting, and that tests thereafter be performed at about twice the age of the previous test. This would require different testing times for each type of cementitious system. This process was simplified for this testing program, and fixed testing times were chosen for each curing temperature. The testing times were determined based on the equivalent age maturity method with an assumed E of 40,000 J/mol. The objective was to test at equivalent maturities for the specimens cured at the three different temperatures. The approximate testing ages used for the different temperatures are presented in Table 1. For some higher early strength mixtures, the

Table 1. Target Testing Ages Used for Different Curing Temperatures

Isothermal batching and curing temperature (°C)	Target testing age (days)					
	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
8	1	2	4	8	14	28
23	0.5	1.67	3	6	11	22
40	0.67 (0.375[a])	1	2	4	6	11

[a]Used for mortars that exhibited a rapid early-age strength development.

age of the first test at the higher curing temperature was critical, because a significant amount of strength development occurred very early. Therefore, earlier test ages were required for an accurate representation of the initial strength development, and these modifications are shown in Table 1.

Mixture Proportions and Cementitious Materials

The mortar testing program outlined above was performed on 11 mixtures, and the equivalent concrete mixtures are summarized in Table 2. The mixture proportions were selected to be representative of concrete pavement mixtures. An ASTM Type I cement (Source A) was chosen to produce a control mixture. The type and proportion of SCMs used with this cement were varied. Class C fly ash and Class F fly ash at replacement dosages of 15, 25, and 35% were tested. An ASTM Grade 120 ground-granulated blast-furnace (GGBF) slag was used at replacement dosages of 30 and 50%. The replacement dosages of the SCMs were determined on a volume basis. Two additional Type I cements, Sources B and C, were also tested. Since 11 mixtures were tested at three different curing temperatures and 18 mortar cubes were made at each temperature, a total of 594 cubes were made and tested.

Results

All data collected in this study are available elsewhere (Schindler 2002). The strength gain data for some of the mixtures are presented in Fig. 3. Behavior concerning the compressive strength development at different temperatures may be identified from Fig. 3. When a Type I cement is considered (Mixture IA), the crossover for a curing temperature of 40°C occurs at an early concrete age of 24 h, and there is about a 30% reduction in the calculated ultimate strength as compared with the mortar cured at 23°C. However, the mortar cured at 8°C shows a 4% increase in the calculated ultimate strength (S_u) as compared to the mortar cured at 23°C. When Type I cement was replaced with 35% Class C fly ash (Mixture C35), the crossover for a curing temperature of 40°C occurs at a concrete age of 160 h. When Type I cement was replaced with 35% Class F fly ash (Mixture F35), the 40°C strength development curve approaches the 23°C curve; however, no crossover occurs in the first 700 h. When Type I cement was replaced with 30% GGBF slag (Mixture S30), no crossover is evident. For all the SCM replacement levels shown in Fig. 3, it is worth noting that the crossover effect does not seem to develop for the cold curing temperature (8°C) relative to 23°C. It may be concluded that the amount of long-term strength reduction due to curing at high temperatures compared with curing at room temperature is influenced by the type and amount of SCMs used in the concrete mixture.

Activation Energy and Datum Temperature Values

The data were analyzed in accordance with the procedure (Section A1.1.8.1) outlined in the Annex of ASTM C 1074. With this method, an average experimental E can be obtained from the best-fit slope of the Arrhenius plot, where the natural logarithm of the rate constant is plotted versus the inverse of the absolute curing temperature. The negative of the slope of the best-fit line on the Arrhenius plot is equal to the E divided by the universal gas constant (R).

The best-fit regression constants for the exponential and hyperbolic strength-maturity relationships for each of the mortars cured at 8, 23, and 40°C were determined and are summarized in Tables 3 and 4. The E values are rounded to the nearest 100 J/mol. It was found that both the hyperbolic and exponential strength-age function accurately model the strength development at all temperatures. The coefficients of determination (r^2) obtained for each best-fit line on the Arrhenius plot are shown in Tables 3 and 4. The lowest r^2 value found for the best-fit line was 0.902. In all cases, a linear relationship accurately represented the data points on the Arrhenius plot.

Table 2. Summary of Mixtures Tested during This Study

Mixture identification	Cementitious system	Cementitious materials content (kg/m^3)	Water-to-cementitious materials ratio
IA	Type I cement—Source A[a]	335	0.37
C15	85% Type I cement (A) and 15% Class C fly ash	335	0.37
C25	75% Type I cement (A) and 25% Class C fly ash	335	0.38
C35	65% Type I cement (A) and 35% Class C fly ash	335	0.38
F15	85% Type I cement (A) and 15% Class F fly ash	335	0.38
F25	75% Type I cement (A) and 25% Class F fly ash	335	0.39
F35	65% Type I cement (A) and 35% Class F fly ash	335	0.40
S30	70% Type I cement (A) and 30% GGBF slag	335	0.38
S50	50% Type I cement (A) and 50% GGBF slag	335	0.38
IB	Type I cement—Source B[b]	307	0.50
IC	Type I cement—Source C[c]	307	0.50

[a]Cement source: Texas Lehigh Cement Company, Buda Plant.

[b]Cement source: Capitol Cement, San Antonio.

[c]Cement source: Alamo Cement Company, San Antonio.

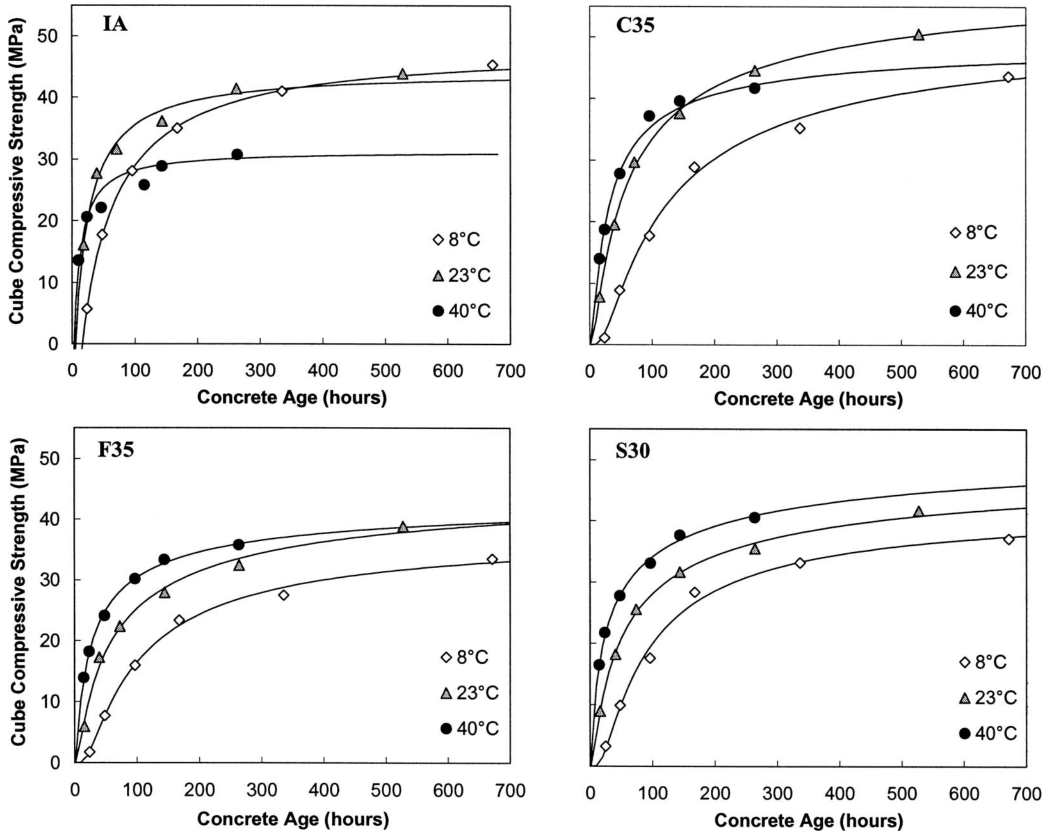

Fig. 3. Compressive strength results for mortar cubes cured at different temperatures

The *E* values of the Type I cements, as calculated using the exponential or hyperbolic strength-age functions, range between 38,300 and 42,300 J/mol, which is close to the lower limit of 40,000 J/mol recommended by ASTM C 1074 for Type I cements. A comparison of the *E* values shown in Tables 4 and 5 indicates that these values can differ between 2 and 38% when either the hyperbolic or exponential strength-age functions are used to evaluate the rate constants. In all cases, the *E* values calculated using the exponential function were greater than the *E* values calculated using the hyperbolic function. This indicates that the choice of strength-age relationship influences the experimental *E*. This was also observed by Pinto (1997), who found different *E* values for different strength-age functions. Based on these results, it is recommended that the strength-maturity relationship used to implement the maturity method should be the same as the strength-age relationship used to determine the mixture-specific *E*.

With regard to the effect of different additions of SCMs on the *E* value, weak trends may be identified in Tables 4 and 5. When the exponential strength-age function is used (Table 3), the following conclusions can be made:

1. The average *E* for the three Type I cements is 40,700 J/mol;
2. When Class C fly ash is used, the average *E* is 44,000 J/mol,

Table 3. Analysis Results Determined with Exponential Strength-Age Function

	$T_c=8°C$			$T_c=23°C$			$T_c=40°C$				
Mix ID	S_u (MPa)	τ (h)	β	S_u (MPa)	τ (h)	β	S_u (MPa)	τ (h)	β	r^2	*E* (J/mol)
IA	49.4	61.11	0.700	48.1	19.6	0.700	32.2	10.7	0.700	0.977	42,300
C15	48.0	74.4	0.760	49.0	21.5	0.760	44.4	10.9	0.760	0.979	46,600
C25	54.8	98.6	0.718	58.2	30.8	0.718	47.7	15.9	0.718	0.981	44,200
C35	52.9	132.3	0.654	61.9	47.4	0.654	49.8	24.2	0.654	0.990	41,300
F15	46.9	63.8	0.904	36.8	18.5	0.904	48.1	9.4	0.904	0.967	43,600
F25	47.2	111.9	0.645	47.5	33.6	0.645	48.3	14.6	0.645	0.986	46,400
F35	38.6	125.4	0.596	48.0	47.4	0.596	44.8	19.6	0.596	1.000	45,000
S30	42.7	61.9	0.583	51.2	41.7	0.583	56.1	11.4	0.583	0.902	40,700
S50	70.1	204.4	0.507	68.4	101.7	0.507	45.2	33.8	0.507	0.987	41,200
IB	46.2	78.4	0.778	49.0	33.3	0.778	41.5	14.3	0.778	1.000	38,900
IC	51.7	51.2	0.812	49.4	23.0	0.812	39.6	9.5	0.812	0.998	40,800

Note: Coefficient of determination (r^2) obtained for the straight-line fit on the Arrhenius plot.

Table 4. Analysis Results Determined with Hyperbolic Strength-Age Function

	$T_c=8°C$			$T_c=23°C$			$T_c=40°C$					
Mix ID	S_u (MPa)	t_0 (h)	K (h^{-1})	S_u (MPa)	t_0 (h)	K (h^{-1})	S_u (MPa)	t_0 (h)	K (h^{-1})	T_0 (°C)	r^2	E (J/mol)
IA	49.1	15.1	0.0167	44.9	4.3	0.0401	31.7	2.6	0.0835	2.0	0.999	39,000
C15	48.7	18.0	0.0130	47.1	3.6	0.0343	43.0	0.0	0.0596	0.0	0.982	37,000
C25	55.1	19.8	0.0097	54.7	4.5	0.0240	43.0	0.0	0.0368	−1.3	0.967	34,500
C35	52.3	20.9	0.0075	56.0	5.4	0.0158	47.2	2.6	0.0317	0.3	1.000	35,000
F15	46.9	17.4	0.0132	36.3	6.4	0.0489	39.4	0.0	0.0735	−0.6	0.909	39,000
F25	44.9	17.5	0.0088	43.9	4.2	0.0226	44.1	0.0	0.0451	1.2	0.989	37,400
F35	38.5	19.3	0.0093	41.4	4.5	0.0171	39.4	0.0	0.0356	−0.6	0.995	32,600
S30	44.5	17.1	0.0095	44.3	1.8	0.0181	43.5	0.0	0.0398	0.8	0.974	34,700
S50	40.1	4.9	0.0048	53.0	3.0	0.0092	39.6	0.0	0.0247	3.2	0.989	37,700
IB	47.6	17.2	0.0112	47.3	5.6	0.0221	41.0	3.5	0.0596	3.4	0.991	38,300
IC	56.7	11.4	0.0121	48.1	5.6	0.0361	36.8	0.2	0.0615	0.7	0.998	39,500

Note: Coefficient of determination (r^2) obtained for the straight-line fit on the Arrhenius plot.

which is 8% higher than the average E obtained for the Type I cements;

3. When Class F fly ash is used, the average E is 45,000 J/mol, which is 11% higher than the average E obtained for the Type I cements; and
4. When GGBF slag is used, the average E is 41,000 J/mol, which is very close to the average E obtained for the Type I cements.

When the hyperbolic strength-age function is used (Table 4), the following conclusions can be made:

1. The average E for the three Type I cements is 38,900 J/mol;
2. When Class C fly ash is used, the average E is 35,500 J/mol, which is 9% lower than the average E obtained for the Type I cements;
3. When Class F fly ash is used, the average E is 36,300 J/mol, which is 7% lower than the average E obtained for the Type I cements; and
4. When GGBF slag is used, the average E is 36,200 J/mol, which is 7% lower than the average E obtained for the Type I cements.

Table 5. Strength Limitations Determined for Equivalent Age Maturity Method

	Relative strength (R_s) over which an accurate estimate is obtained	
Mixture ID	$T_c=8°C$ (%)	$T_c=40°C$ (%)
IA	40–100	0
C15	34–100	0
C25	42–100	0
C35	56–100	0
F15	38–100	0
F25	22–100	0–100
F35	20–100	0–100
S30	42–100	0–100
S50	0–28	0
IB	26–100	0
IC	43–100	0

Note: R_s=ratio of the strength relative to the 28-day strength at the reference curing temperature.

The datum temperature (T_0), as computed by analyzing the data with the hyperbolic strength-age function for use with the Nurse–Saul maturity function, is shown in Table 4. In the original definition of the Nurse–Saul maturity function, a datum temperature of −10.5°C was recommended (Saul 1951). ASTM C 1074 recommends a datum temperature of 0°C for a Type I cement. The calculated datum temperatures ranged between values of −1.3 and 3.4°C. The datum temperature for six of the 11 mixtures was within ±1.0°C of 0°C.

Evaluation of Accuracy of Maturity Method

The classical maturity method was implemented in this study by using the strength-maturity relationship obtained at 23°C, and then estimating the strength development at curing temperatures of 8 and 40°C. Fig. 4 compares the strengths as estimated by the equivalent age maturity method with the measured strength at 8 and 40°C for four of the mixtures of this study. All strengths are estimated through the use of the hyperbolic strength-maturity relationship and with the mixture-specific E values as listed in Table 4. It should be noted that the accuracy obtained is approximately the same when the exponential strength-maturity function is used. If the strength values are accurately estimated, the plot of measured versus estimated strengths should fall on the solid 45° lines shown in Fig. 4.

Note that for all four mixtures, the test points obtained at 23°C are expected to fall close to the 45° line, as this reflects the scatter of the data about the best-fit strength-maturity relationship determined at 23°C. From the location of the data points of the specimens cured at 40°C for Mixtures IA and C35, it may be concluded that the strength is overestimated by the maturity method at all ages for the high curing temperatures. Additional lines to assess the accuracy of the strength estimates are also provided in Fig. 4; these lines correspond to a ±10 and ±20% error. For curing temperatures of 40°C, the strength is overestimated by more than 20 and 10% for Mixtures IA and C35, respectively.

When curing at 8°C for Mixtures IA and C35 is considered, the estimated strength is within a 10% error range, except for the first two data points. In fact, for Mixture IA, the strength is underestimated at later ages. The very first strength point collected for curing at 8°C was overestimated for ten of the 11 mixtures evaluated. This may be attributed to the fact that the time when

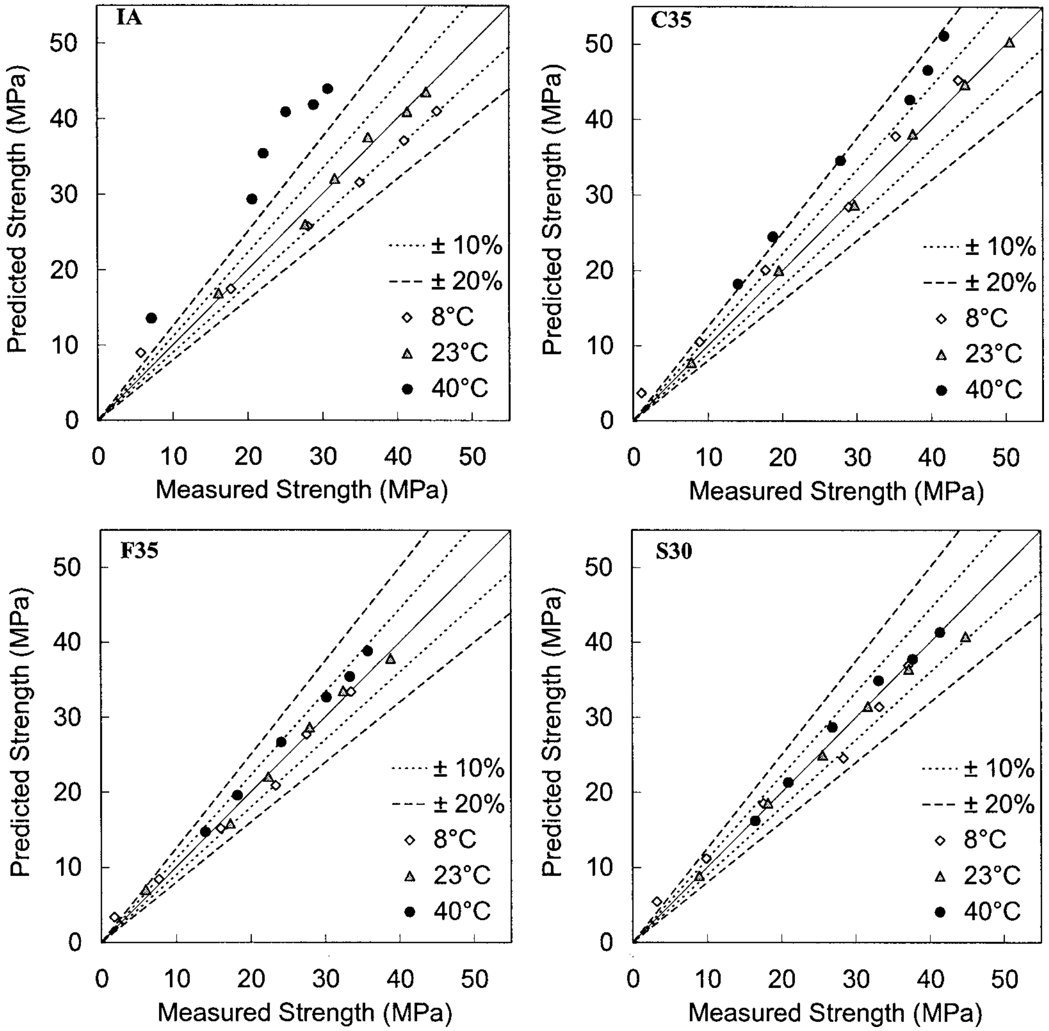

Fig. 4. Measured strength versus strength estimated with equivalent age maturity method

the strength development begins (t_0), is not properly characterized by the maturity method when the hyperbolic strength-age function is used for curing at 8 °C.

The accuracies of the strength estimates for Mixtures F35 and S30, at both 8 and 40 °C, are significantly higher than the accuracies obtained for Mixtures IA and C35. For Mixtures F35 and S30, all of the strengths estimated at 8 and 40 °C are within a 10% error range; except for the first test point at 8 °C. The reason for the improved accuracy in the estimate may be explained by evaluating the magnitude of the crossover effect for each mixture shown previously in Fig. 3. Both Mixtures IA and C35 exhibited significant crossover at a temperature of 40 °C, and the estimated strengths at this curing temperature were significantly overestimated by the maturity method. On the contrary, Mixtures F35 and S30 did not exhibit a crossover effect, and for these mixtures the maturity method more accurately estimated the strength at 8 and 40 °C.

The crossover effect has been used to explain the accuracy associated with the estimated strength, creating the need to apply a strength limitation when the classical maturity method is used. This conclusion is similar to that found by other researchers that recommended a strength limitation above which the maturity method will not yield conservative estimates of the strength (Kjellsen and Detwiller 1993; Byfors 1980; Jonasson 1988; Emborg 1989; Pane and Hansen 2002). Some of these limits were discussed in the "Introduction" section of this paper.

Under cold curing temperature conditions, the strength obtained may exceed the strength obtained should the concrete be cured at the higher reference temperature. This effect occurs for Mixture IA as shown in Fig. 3. This may allow for a less stringent strength limitation to be used when estimating the strength of concrete cured at low temperatures relative to the strength limitation when estimating the strength at high temperatures. In some instances, strength limitations for specimens cured at low temperatures may not be required, since a conservative estimate of the strength may be determined by the maturity method.

A 10% overestimation is assumed to be the limiting criterion to determine the strength range over which the classical maturity method provides an accurate estimate of the measured strength. With this criterion, it may be seen in Fig. 4 that for Mixture IA there is no strength range where the classical maturity method provides an accurate estimate of the strength of the specimens cured at 40 °C. However, for the specimens cured at 8 °C, the equivalent age maturity method provides a sufficiently accurate estimate for all strengths higher than 18 MPa. For this curing temperature, it may further be seen that for strengths higher than 18 MPa, the strength is slightly underestimated, which is conservative. The 28-day strength for the specimens cured at 23 °C was

44 MPa. The strength range over which an accurate estimation is obtained will be expressed as a percentage (R_s) of the 28-day strength when cured at 23°C. Based on the discussion above, the recommendations for Mixture IA (Type I cement) are as follows:

1. For the curing temperature of 8°C: Sufficiently accurate strength estimates are achievable with the equivalent age maturity method within the strength range (R_s) of 40–100%; and
2. For the curing temperature of 40°C: The equivalent age maturity method should not be applied at these curing temperatures, i.e., $R_s=0\%$.

A summary of the recommended limits for each of the mixtures when the equivalent age maturity method is evaluated is provided in Table 5. It should be noted that for eight of the 11 mixtures studied, the equivalent age maturity method is not recommended to estimate the strength for curing at 40°C. Only for Mixtures F25, F35, and S30 would the equivalent age maturity method provide sufficiently accurate estimates for curing at 40°C; these are also the mixtures that exhibited little or no strength crossover. Table 5 also reveals that for curing at 8°C there is a significant range over which the classical maturity method provides accurate strength estimates. If the first test point is neglected, the strength for curing at 8°C was accurately estimated at all ages for seven of the mixtures. Only for Mixtures C25, C35, and S30 was the strength overestimated by more than 10% at ages greater than the first testing age.

Another way of considering the results obtained for the strength estimates at the high temperatures is to conclude that the temperature at which the strength-maturity relationship was obtained ($T_r=23°\text{C}$) is too far removed from the temperature (40°C) at which the estimate is required. In order to use the classical maturity method at this high curing temperature, it is recommended that the strength-maturity relationship be developed from specimens cured closer to the anticipated early-age temperature range that the in-place concrete will experience. For example, if the early-age in-place temperatures are expected to vary between 30 and 45°C, it is recommended that the strength-maturity relationship be determined at 35°C or under field-curing conditions. This will reduce the difference between the reference temperature and the high curing temperature, which will reduce the temperature adjustment required for the equivalent age maturity method. The strength-maturity relationship established at a temperature closer to the in-place curing temperatures will account for long-term strength reduction due to high curing temperatures (inherent crossover effect), and this should result in more accurate estimates of the in-place concrete strength.

Summary and Conclusions

Compressive strength versus age data were collected by testing sets of mortar cubes that were wet cured at isothermal temperatures of 8, 23, and 40°C. Eleven mixtures were used to study the effect of different cements, fly ash classes, and ground-granulated blast-furnace slag on the strength development when cured at different temperatures. Based on the compressive strength data, it may be concluded that the amount of long-term strength reduction due to curing at high temperatures compared with curing at room temperature is influenced by the type and amount of supplementary cementing materials used in the concrete mixture. Mixtures made with only portland cement exhibited large strength reductions due to curing at high temperatures.

Datum temperature and activation energy (E) values were determined in accordance with ASTM C 1074 (ASTM 2004) for each of the mixtures. Since ASTM only provides recommendations when Type I cement mixtures are used, the values in Tables 3 and 4 may be a useful reference when datum temperature and activation energy values are required for mixtures with cementitious systems other than only Type I cement. The E values determined for the Type I cements ranged between 38,300 and 42,300 J/mol. The calculated datum temperatures ranged between values of −1.3 and 3.4°C. The datum temperature for six of the 11 mixtures was within ±1.0°C of 0°C.

Both the hyperbolic and exponential strength-age relationships accurately model the strength development at all temperatures. Results indicate that the choice of strength-age relationship significantly influences the experimental E determined from ASTM C 1074. It is recommended that the strength-maturity relationship used to implement the maturity method should be the same as the strength-age relationship used to determine the mixture-specific E.

The accuracy of the equivalent age maturity method was evaluated based on the data collected. It is shown that in many cases the equivalent age maturity method overestimates the strength at curing temperatures of 8 and 40°C when the strength-maturity relationship is defined by only using strength data obtained at 23°C. Based on the test results obtained, strength limits between which the classical equivalent age maturity method provides an overestimate of 10% or less were determined. The fact that a poor estimate is obtained at high curing temperatures is because of the loss in long-term strength that occurs when curing some mixtures at high temperatures. The estimation error results from the fact that the temperature at which the strength-maturity relationship is established results in a higher estimate of the long-term strength than is actually measured at high curing temperatures. A more accurate estimate will be obtained if the strength-maturity relationship is established at a temperature closer to the temperature at which strength estimates are required.

Notation

The following symbols are used in this paper:

E = activation energy (J/mol);
K = rate constant for hyperbolic strength-maturity relationship (h^{-1});
M = maturity of the concrete (°C h);
R = universal gas constant (8.3144 J/mol/K);
R_s = compressive strength relative to 28-day strength when cured at 23°C(%);
S = compressive strength (MPa);
S_u = ultimate compressive strength (MPa);
T_c = average concrete temperature during time interval (°C);
T_r = reference temperature (°C);
T_0 = datum temperature (°C);
t = chronological age (h);
t_e = maturity in terms of equivalent age (h);
t_0 = age when strength development begins (h);
β = shape constant for exponential strength-maturity relationship (unitless);
Δt = chronological time interval between temperature measurements (h); and
τ = time constant for exponential strength-maturity relationship (h).

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