THE MATURITY METHOD: FROM THEORY TO APPLICATION

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The Maturity Method: From Theory to Application[1]

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Abstract

The maturity method is a technique to account for the combined effects of time and temperature on the strength development of concrete. The method provides a relatively simple approach for making reliable estimates of in-place strength during construction. The origin of the method can be traced to work on steam curing of concrete carried out in England in the late 1940s and early 1950s. As a result of technology transfer efforts by the Federal Highway Administration, there is renewed interest in the method within the United States. The purpose of this paper is to review of the basic concepts underlying the method and to explain how the method is applied. The review focuses on work carried out by researchers at the National Institute of Standards and Technology (formerly the National Bureau of Standards).

Introduction

On March 2, 1973, portions of a multi-story apparent building, under construction in Fairfax County, Va., suffered a progressive collapse. Fourteen workers were killed and 34 were injured in the accident. The National Bureau of Standards (NBS) was requested by the Occupational Safety and Health Administration (OSHA) to assist in determining the technical cause of the collapse. The NBS report concluded that the most probable cause of the failure was premature removal of formwork that resulted in punching shear stresses that exceeded the capacity of the relatively young concrete [Carino et al. 1983a]. At the time of the failure, the concrete in the floor slab where failure is believed to have initiated was only four days old. During that period, the average temperature recorded at a nearby airport had averaged about 7 °C. The NBS investigators encountered difficulty in using published relative strength development data obtained under constant temperature conditions to obtain a reliable estimate of the in-place concrete strength at the time of the failure. This triggered an interest in a relatively new approach known as the *maturity method* for estimating in-place strength development under variable temperature conditions.

The maturity method relies on the measured temperature history of the concrete to estimate strength development during the curing period, when moisture is available for cement hydration.

The temperature history is used to calculate a quantity called the *maturity index*. For each concrete mixture, the relationship between strength (or other property of interest) and the maturity index is established beforehand. The strength relationship and the measured in-place maturity index are used to estimate the in-place strength.

The initial research at NBS confirmed that the maturity method could be used to estimate the development of compressive strength, and other mechanical properties of concrete, under different curing temperatures [Lew and Reichard 1978a, 1978b]. In this early work, the initial concrete temperature was the same for all specimens, and specimens were moved into the different temperature chambers after molding had been completed.

In a later study at NBS, the applicability of the maturity method under simulated field conditions was investigated [Carino et al. 1983b]. Three different concrete mixtures were used to fabricate slabs containing push-out cylinder molds [ASTM C 873]. In addition, push-out cylinder molds were filled with concrete and stored in a moist curing room. The slabs were cured outdoors (during the spring). The objective was to determine whether the strength-maturity relationships for the concrete in the field-cured push-out cylinders were the same as those for the companion laboratory-cured cylinders. The results of this study were perplexing: for one mixture there was good agreement between the strengths of field-cured and lab-cured specimens at equal maturities. For the other two mixtures there were significant differences. Examination of the temperature histories of all specimens revealed that, for those two mixtures, the outdoor-cured specimens experienced different early-age concrete temperatures than the lab-cured specimens. For equal values of the maturity index, specimens with higher early-age temperatures resulted in higher initial strengths and lower long-term strength. This “crossover” behavior is illustrated in Fig. 1. Therefore, it appeared that a given concrete mixture does not posses a unique strength-maturity relationship; this behavior had been reported earlier by others [McIntosh 1956; Kleiger 1958].

On April 27, 1978, there was a major construction failure of a cooling tower being constructed in Willow Island, WV. The incident resulted in the death of 51 workers, who were on the scaffolding system that was anchored to the partially completed shell. The NBS was again requested to assist OSHA in determining the technical cause of the failure. The investigators concluded that the most likely cause of the collapse was insufficient concrete strength to support the applied construction loads [Lew 1980]. At the time of the failure, the previous lift of concrete in the shell was only one day old and had been exposed to an estimated average ambient temperature less than 10 °C. This failure convinced NBS researchers that there was an urgent need for standards on estimating in-place concrete strength during construction. Thus NBS staff began an in-depth study of the maturity method. The objective was to gain an understanding of the cause of the “crossover” effect and to develop alternative procedures to eliminate the problem [Carino 1981; Carino and Lew 1983; Carino 1982; Carino 1984]. The NBS research laid the foundation for the development of first standard in the world on the application of the maturity method [ASTM C 1074].

In the mid to late 1990s, the Federal Highway Administration undertook efforts to publicize products resulting from the Strategic Highway Research Program (SHRP). While there was no new research on the maturity method, SHRP Project C-204 recommended this method as an existing technology for estimating in-place strength development in highway structures. The FHWA’s Office of Technology Applications assembled a trailer that was driven throughout the U.S to demonstrate the new technologies to state highway engineers. As a result of this effort,

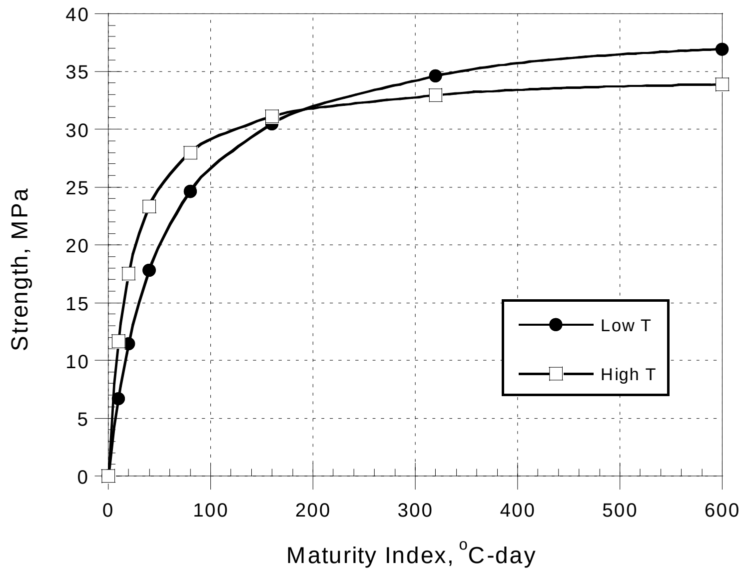

Fig. 1— The "crossover effect" due to different early-age concrete temperature during development of the strength-maturity relationship

many state departments of transportation showed interest in incorporating this method into their standard practices (see for example Myers, 2000).

The purpose of this paper is to provide the reader with an understanding of the basis of the maturity method and to explain how it is implemented. Carino [1991] provides a comprehensive review of the history of the method, its theory, its limitations, and some of its applications.

Background

The origins of the maturity method can be traced to a series of papers from England dealing with accelerated curing methods [McIntosh, 1949; Nurse, 1949; Saul, 1951]. There was a need for a procedure to account for the combined effects of time and temperature on strength development for different elevated temperature curing methods. It was proposed that the product of time and temperature could be used for this purpose. These ideas led to the famous *Nurse-Saul maturity function*:

$$M = \sum_{0}^{t} (T - T_0)\,\Delta t \qquad (1)$$

where

- M = maturity index, °C-hours (or °C-days),
- T = average concrete temperature, °C, during the time interval Δt,
- T_o = datum temperature (usually taken to be -10 °C),
- t = elapsed time (hours or days), and
- Δt = time interval (hours or days).

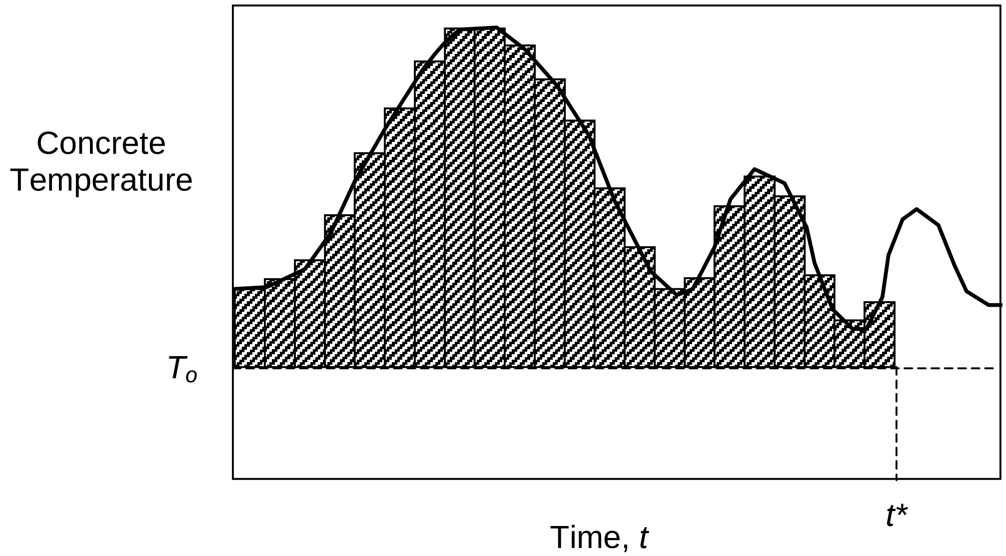

Fig. 2—Schematic of temperature history and temperature-time factor computed according to Eq. (1).

The index computed by Eq. (1) was called the *maturity*, however, the current terminology is the *temperature-time factor* [ASTM C 1074]. Figure 2 shows a schematic temperature history and the temperature-time factor computed according to Eq. (1). The temperature-time factor at some age t^* equals the area below the temperature curve and the datum temperature. In the original proposal, the datum temperature was taken to be the temperature below which strength development ceases. The traditional value for the datum temperature is –10 ºC.

Saul [1951] presented the following principle that has become known as the *maturity rule*:

"*Concrete of the same mix at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity*."

Equation (1) is based on the assumption that the initial rate of strength gain (during the acceleratory period[2] that follows setting) is a linear function of temperature [Carino 1984, 1991]. Soon after the introduction of Eq. (1), it was realized that this linear approximation might not be valid when curing temperatures vary over a wide range. As a result, other researchers proposed a series of alternatives to the Nurse-Saul function [Malhotra, 1971; Carino, 1991]. None of the alternatives, however, received widespread acceptance, and the Nurse-Saul function was used worldwide until an improved function was proposed in the late 1970s.

In 1977, Freiesleben Hansen and Pedersen [1977] proposed a new function to compute a maturity index from the recorded temperature history of the concrete. This function was based on the Arrhenius equation [Brown and LeMay, 1988] that is used to describe the effect of temperature on the rate of a chemical reaction (this is discussed further). The new function allowed the computation of the *equivalent age* of concrete as follows:

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[2] After cement and water are mixed together, there is a time delay before strength development begins. This period is called the induction period. After the induction period there is rapid strength development, and this is the acceleratory period.

$$t_e = \sum_0^t e^{\frac{-E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \Delta t \tag{2}$$

where

t_e = the equivalent age at the reference temperature,

E = apparent activation energy, J/mol,

R = universal gas constant, 8.314 J/mol-K,

T = average absolute temperature of the concrete during interval Δt, Kelvin, and

T_r = absolute reference temperature, Kelvin.

By using Eq. (2), the actual age of the concrete is converted to its equivalent age, in terms of strength gain, at the reference temperature. In European practice, the reference temperature is usually taken to be 20 °C, whereas in North American practice it is usually taken to be 23 °C. The introduction of this function overcame one of the main limitations of the Nurse-Saul function because it allowed for a non-linear relationship between the initial rate of strength development and curing temperature. This temperature dependence is described by the value of the apparent activation energy, *E*.

Comparative studies showed that this new maturity function is superior to the Nurse-Saul function [Byfors, 1980; Carino, 1982]. The use of Eq. (2) largely eliminated the discrepancies between strength-maturity relationships developed with different initial curing temperatures, that is, it eliminated the discrepancy at early maturity shown in Fig. 1. The new function, however, is not able to account for the effects of early-age temperature on the later-age strength (see Carino [1991] for a discussion on the cause of this effect). This is an inherent limitation of the maturity method, and is discussed in the section "Strength Development Relationships."

Effect of Temperature on Strength Gain

The key parameter in Eq. (2) is the "*activation energy*" that describes the effect of temperature on the rate of strength development. In the early 1980s, the first author began a series of studies to gain a better understanding of the maturity method [Carino, 1984]. From this work, a procedure was developed to obtain the "*activation energy*" of a given cementitious mixture. The procedure is based on determining the effect of curing temperature on the rate constant for strength development. The rate constant is related to the curing time needed to reach a certain fraction of the long-term strength, and can be obtained by fitting an appropriate equation to the strength versus age data acquired under constant temperature (isothermal) curing. The procedure to determine the "*activation energy*" includes the following steps:

- Cure mortar specimens at different constant temperatures.
- Determine compressive strengths at regular age intervals.
- Determine the value of the rate constant at each temperature by fitting a strength-age relationship to each set of strength-age data.
- Plot the natural logarithms of the rate constants versus the inverse of the curing temperature (in Kelvin).
- Determine the best-fit Arrhenius equation (to be explained, see Eq. (4)) to represent the variation of the rate constant with the temperature.

By using the above procedure, the "*activation energy*" was determined for concrete and mortar specimens made with different cementitious materials [Tank and Carino, 1991; Carino and Tank, 1992]. It was found that for concrete with water-cement ratio (*w/c*) = 0.45, the "*activation energy*" ranged from 30 and 64 kJ/mol; while for *w/c* = 0.60 it ranged from 31 to 56 kJ/mol, depending on the type of cementitious materials and admixtures.

The significance of the "*activation energy*" is explained further. In Eq. (2), the exponential term within the summation converts increments of curing time at the actual concrete temperature to equivalent increments at the reference temperature. Thus the exponential term can be considered as an *age conversion factor*, γ:

$$\gamma = e^{\frac{-E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \tag{3}$$

Figure 3 shows how the age conversion factor varies with curing temperature for different values of the "*activation energy*". (Note that in Eq. (3), absolute temperature is used.) The reference temperature is taken as 23 °C (≈296 K). It is seen that for an "*activation energy*" of 30 kJ/mol, the age conversion factor is nearly a linear function of temperature. In this case, the Nurse-Saul equation would be a reasonably accurate maturity function to account for the combined effects of time and temperature, because the Nurse-Saul function assumes that the rate constant varies linearly with temperature [Carino, 1984]. For an "*activation energy*" of 60 kJ/mol, the age conversion factor is a highly non-linear function of the curing temperature. In this instance, the Nurse-Saul function would be an inaccurate maturity function. In summary, Fig. 3 shows the nature of the error in the age conversion factor if the incorrect value of activation energy were used for a particular concrete mixture. The magnitude of the error would increase with increasing difference of the curing temperature from 23 °C.

The reader will have noticed that the term "*activation energy*" has been used within quotation marks. This is because the E-value that is determined when the rate constant is plotted as a function of the curing temperature is not truly an activation energy as implied by the Arrhenius

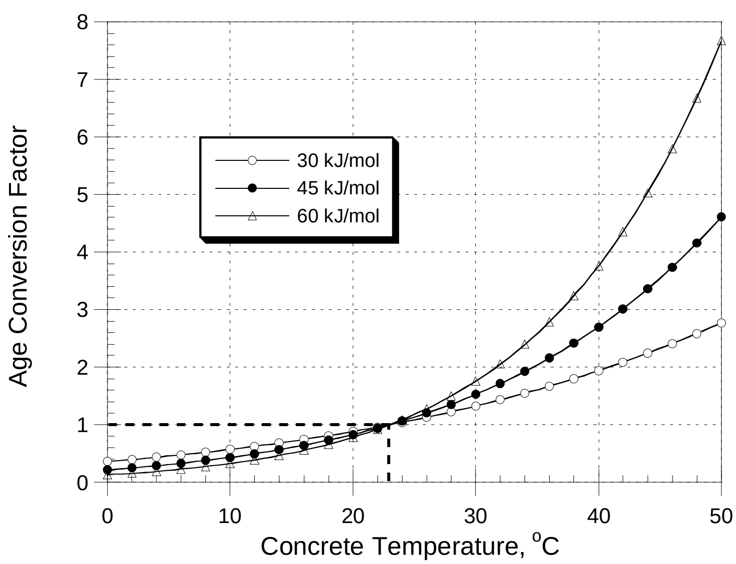

Fig. 3— Age conversion factor according to Eq. (3) for different values of apparent activation energy

equation. The following discussion is provided for those unfamiliar with the concept of activation energy or the origin of the Arrhenius equation.

The idea of "*activation energy*" was proposed by Svante Arrhenius in 1888 to explain why chemical reactions do not occur instantaneously when reactants are brought together, even though the reaction products are at a lower energy state [Brown and LeMay, 1988]. Arrhenius proposed that before the lower energy state is achieved, the reactants must have sufficient energy to overcome an energy barrier separating the unreacted and reacted states. A physical analogy is brick standing upright. The brick is in a lower energy state when lying horizontal, but it will not instantaneously tip over to this lower energy state. It must be pushed from the higher to the lower energy state. The energy required to push the brick from it upright position to the point of instability, after which the brick falls on its own, is the activation energy for this process.

For molecular systems, the reactant molecules are in constant motion and energy is transferred between them as they collide [Brown and LeMay, 1988]. A certain number of molecules will acquire sufficient energy to surmount the energy barrier and form the lower energy reaction product. As the system is heated, the kinetic energy of the molecules increases and more molecules will surmount the barrier. Thus the rate of reaction increases with increasing temperature. Arrhenius observed that the rate constant, *k*, of many reactions increased with temperature according to what has since been called the Arrhenius equation, as follows:

$$k = A\, e^{\frac{-E}{RT}} \tag{4}$$

The term *A* is called the *frequency factor* and is related to the frequency of collisions and the probability that the molecules will be favorably oriented for reaction [Brown and LeMay, 1988]. It can be seen that the age conversion factor given by Eq. (2) is the ratio of the rate constants at two different temperatures.

The Arrhenius equation was derived empirically from observations of homogeneous chemical systems undergoing a single reaction. Roy and Idorn [1982] have noted that researchers "*... have cautioned that since cement is a multiphase material and also the process of cement hydration is not a simple reaction, homogeneous reaction kinetics cannot be applied.*" Thus the "*activation energy*" obtained from strength gain data or degree of hydration data is not a true activation energy for a single reaction as originally proposed by Arrhenius. This is why quotation marks have been used.

The authors believe that the Arrhenius equation happens to be one of several equations that can be used to describe the variation of the rate constant for strength gain (or degree of hydration) with curing temperature. This was the motivation for a simpler function than Eq. (2) to compute equivalent age [Carino, 1982; Tank and Carino, 1991; Carino and Tank, 1992]. It is suggested that the following exponential equation can represent the temperature dependence of the rate constant for strength gain:

$$k = A_0\, e^{BT} \tag{5}$$

where

A_0 = the value of the rate constant at 0 °C,

B = temperature sensitivity factor, 1/°C, and

T = concrete temperature, °C.

Based on Eq. (5) and the fact that the age conversion factor is a ratio of rate constants, the equation for equivalent age at the reference temperature T_r is as follows:

$$t_e = \sum_0^t e^{B(T-T_r)} \Delta t \tag{6}$$

where

B = temperature sensitivity factor, 1/°C

T = average concrete temperature during time interval Δt, °C, and

T_r = reference temperature, °C.

It was shown that Eqs. (2) and (6) would result in similar values of equivalent age [Carino, 1992]. The authors believe, however, that Eq. (6) has the following advantages over Eq. (2):

- The temperature sensitivity factor, *B*, has more physical significance compared with the apparent activation energy: for each temperature increment of 1/*B*, the rate constant for strength development increases by a factor of approximately 2.7.
- Temperatures do not have to be converted to the absolute temperature scale.
- Equation (6) is a simpler than Eq. (2).

Strength Development Relationships

The key to developing the most appropriate maturity function for a particular concrete mixture is to determine the variation of the rate constant with curing temperature. As was mentioned, the rate constant is related to the rate of strength gain at a constant temperature, and it can be obtained from an appropriate equation of strength gain versus age. Thus it is necessary to consider some of the relationships that have been used to represent strength development of concrete.

The authors have used successfully the following hyperbolic equation for strength gain under isothermal curing up to equivalent ages at 23 °C of about 28 days:

$$S = S_u \frac{k(t-t_0)}{1+k(t-t_0)} \tag{7}$$

where

S = strength at age t,

S_u = *limiting strength*,

k = rate constant, 1/day, and

t_0 = age at start of strength development.

The basis of this equation has been explained elsewhere [Carino, 1984; Knudsen, 1980]. Equation (7) assumes that strength development begins at age t_0. Thus the period of gradual strength development during setting is not considered. The parameters S_u, k, and t_0 are obtained by least-squares curve fitting to strength versus age data. The *limiting strength*, S_u, is the asymptotic value of the strength for the hyperbolic function that fits the data. As is discussed below, the best fit value for S_u does not necessarily represent the actual long-term strength of the concrete, and that is why the italic font is used in the above definition. For the hyperbolic model, the rate constant has the following property: when the age beyond t_0 is equal to $1/k$, the strength equals 50 % of the *limiting strength*, S_u.

An equation similar to Eq. (7) was also used by Knudsen [1980] and Geiker [1983] to represent the degree of hydration and development of chemical shrinkage as a function of age. Geiker [1983], however, noted that Eq. (7) gave a poor fit for certain cementitious systems. It was found that the following version of the hyperbolic equation gave a better fit to that data than Eq. (7) [Knudsen, 1984]:

$$S = S_u \frac{\sqrt{k(t-t_0)}}{1+\sqrt{k(t-t_0)}} \tag{8}$$

Knudsen [1984] explained the differences between Eq. (7) and Eq. (8) in terms of the hydration kinetics of individual cement particles. Equation (7) is based on *linear kinetics,* which means that the degree of hydration of an individual cement particle is a linear function of the product of time and the rate constant. Equation (8) is based on *parabolic kinetics,* which means that the degree of hydration is a function of the *square root* of the product of time and the rate constant. Thus Eqs. (7) and (8) are called the *linear hyperbolic* and *parabolic hyperbolic* models.

Freiesleben Hansen and Pedersen [1985] proposed the following exponential equation to represent strength development of concrete under isothermal curing:

$$S = S_u e^{-\left(\frac{\tau}{t}\right)^{\alpha}} \tag{9}$$

where

t = age

τ = a time constant and

α = a shape parameter.

This equation can model gradual strength development during the setting period and it is also asymptotic to a limiting strength. The time constant τ represents the age at which the strength has reached 0.37 S_u. Thus the value of $1/\tau$ is the rate constant for this equation. The shape parameter α affects the slope of the curve during the acceleratory period and it affects the rate with which the strength approaches the limiting strength [Carino, 1991].

Examples are presented to illustrate the performance of Eqs. (7), (8), and (9) in representing actual strength development data. Figure 4(a) shows strength data for mortar cubes cured at room temperature and tested at ages from 0.4 to 56 days. Figure 4(b) shows data for standard-cured concrete cylinders tested at ages from 7 days to 3.5 years [Carette and Malhotra, 1991]. The curves are the best-fit curves for Eqs. (7), (8), and (9). For the mortar data, the linear hyperbolic function and the exponential function fit the data well, and these curves are nearly indistinguishable in Fig. 4(a). For the concrete data, the parabolic hyperbolic function and the exponential function fit the data well and these curves cannot be distinguished in Fig. 4(b).

The results shown in Fig. 4 highlight the capabilities of the various strength-age functions. The linear hyperbolic function appears to be a good model for strength development up to about 28 days (equivalent age) but not for later ages. The parabolic hyperbolic model appears to be better suited for modeling later age strength gain. The exponential model appears to be capable of modeling strength gain over the full spectrum of ages.

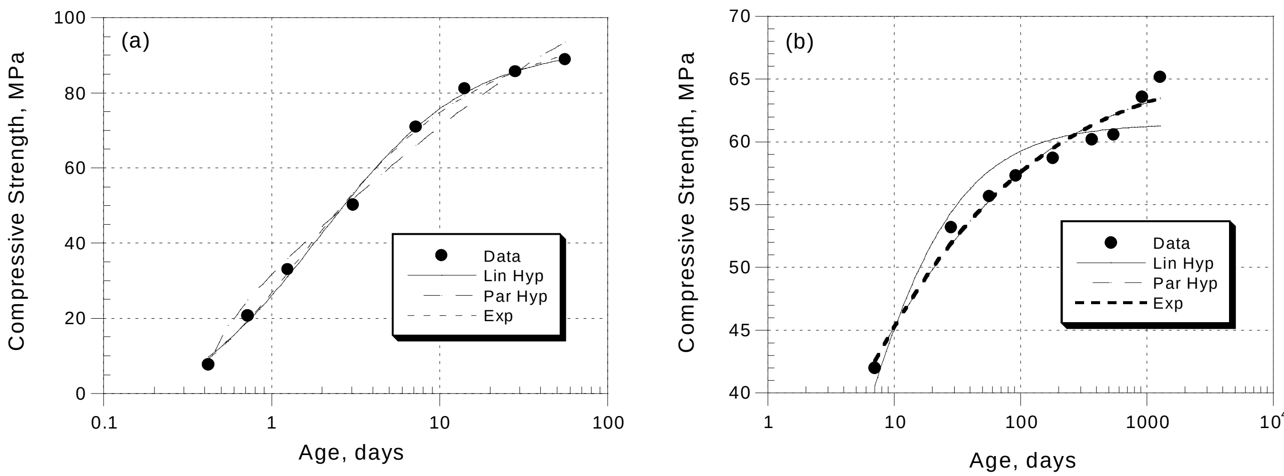

Fig. 4—Fit of strength-age models to data: (a) mortar cubes and (b) concrete cylinders

The inherent limitation of the linear hyperbolic function can be understood by considering the ratio of the *limiting strength* to the 28-day strength. If the t_0-term in Eq. (7) is neglected, the following equation is obtained for this ratio:

$$\frac{S_u}{S_{28}} = \beta = 1 + \frac{1}{28k} \qquad (10)$$

Thus the value of β is directly related to the rate constant. A higher value of k results in a lower value of β, which means a smaller difference between the *limiting strength* and the 28-day strength. The rate constant is, in turn, controlled primarily by the initial rate of strength development. The fact is that the ratio of actual long-term strength of concrete to the 28-day strength does not obey Eq. (10). This means that value of S_u obtained by fitting the linear hyperbolic model to strength-age data will be lower than the actual long-term strength of concrete if allowed to cure for a long time.

Based on the above discussion, one might conclude that the exponential model given by Eq. (9) is the best for determining the rate constant at a particular curing temperature. This would be correct if the shape parameter, α, were independent of the curing temperature. Test results show that this is not always the case [Carino et al., 1992]. Thus a maturity function based solely upon the variation of the rate constant ($1/\tau$) with temperature would not be able to account accurately for the combined effects of time and temperature on strength development.

Which strength-development model should be used? The maturity method is used typically to monitor strength development during construction. Therefore, it is not necessary to model accurately the strength gain at later ages. The authors believe that the linear hyperbolic model can be used to analyze strength data, up to a 28-day equivalent age, to determine the variation of the rate constant with curing temperature. Knudsen[3] suggests that the linear hyperbolic model is suitable up to a degree of hydration of 85 %. The suitability of the linear hyperbolic model was also demonstrated in a recent study on the applicability of the maturity method to mortar

[3] T. Knudsen, The Technical University of Denmark, April 1985, personal communication

mixtures with low water-cementitious materials ratios, typical of those in *high-performance concrete* [Carino et al., 1992].

In-place Strength

The maturity method is generally used to estimate the in-place strength of concrete by using the in-place maturity index and a previously established relationship between maturity index and strength. This assumes that a given concrete possesses a unique relationship between strength and the maturity index. This assumption would be acceptable if the long-term strength of concrete were independent of the curing temperature, but this is not the case. It is known that the initial temperature of the concrete affects the long-term strength [Verbeck and Helmuth, 1968]. Thus if the same concrete mixture were used for a cold weather placement and a hot weather placement, the strength would not be the same for a given maturity index. It is proposed that the correct application of the maturity method is to estimate *relative strength*. Tank and Carino [1991] proposed the following *rate constant* model of relative strength development, S/S_u, in terms of equivalent age t_e:

$$\frac{S}{S_u} = \frac{k_r(t_e - t_{0r})}{1 + k_r(t_e - t_{0r})} \qquad (11)$$

where

k_r = value of the rate constant at the reference temperature, and

t_{0r} = age at start of strength development at the reference temperature.

Equation (11), leads to the following modified maturity rule [Carino 1991]:

Samples of a given concrete mixture which have the same equivalent age and which have had a sufficient supply of moisture for hydration will have developed equal fractions of their limiting strength irrespective of their actual temperature histories.

The previous discussion, however, has shown that, for the linear hyperbolic model, the ratio S/S_u may not indicate the true fraction of the long-term strength because the calculated value of S_u may not be the actual long-term strength. This deficiency can be overcome by expressing relative strength as a fraction of the strength at an equivalent age of 28-days. By using the definition of β in Eq. (10), the relative strength gain equation would be as follows:

$$\frac{S}{S_{28}} = \beta \frac{k_r(t_e - t_{0r})}{1 + k_r(t_e - t_{0r})} \qquad (12)$$

The value of **β** would be obtained as follows:

- Fit Eq. (7), to the data of strength versus equivalent age.
- Estimate the strength at an equivalent age of 28 days, S_{28}, from the best-fit equation.
- Divide the value of S_u by S_{28}.

By using Eq. (12) and the measured in-place equivalent age, one can estimate the fraction of the 28-day strength that will have developed. It is, however, not possible to estimate S_{28} without additional testing of the concrete. This is an inherent limitation in the application of the maturity method.

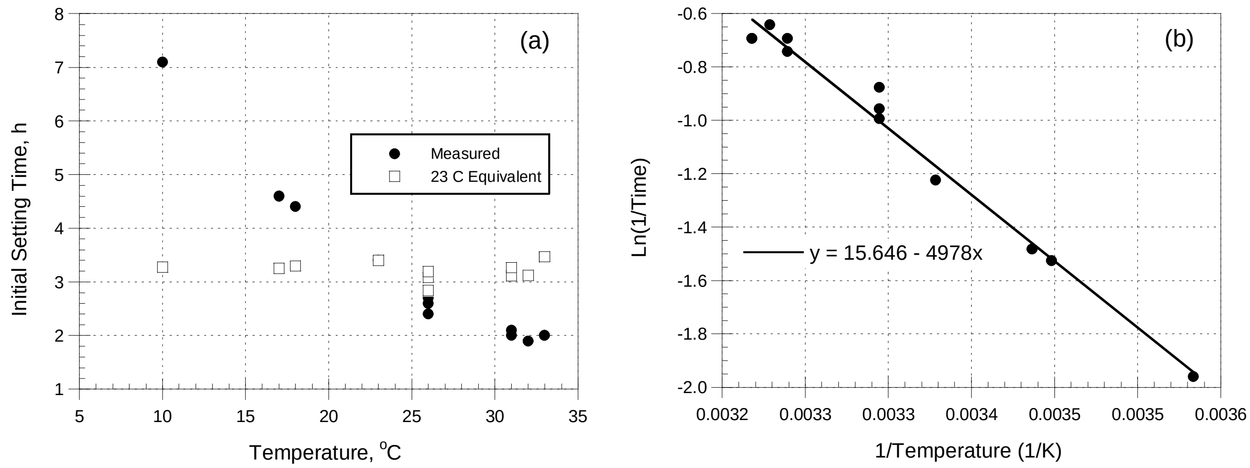

Fig. 5—a) Initial setting time versus temperature; b) plot of natural logarithm of inverse of setting time versus inverse of absolute temperature (Pinto and Hover 1999)

Setting Time and Maturity

Pinto and Hover (1999) investigated whether the maturity method was applicable to the setting time of concrete measured in accordance with ASTM C 403/C 403M. The solid circles in Figure 5(a) show the reported initial setting times as a function of the average temperature. They found that the setting time at different temperatures could be used to obtain an apparent activation energy to represent the temperature dependence of setting time. The inverses of the setting times were used as rate constants, and the natural logarithms of the rate constants were plotted as a function of the inverse of absolute temperature. As shown in Fig. 5(b), a straight line can be fitted to the transformed data. The slope of the line represents the negative of the apparent activation energy divided by the gas constant (Eq. (2)), and is referred to as Q in ASTM C 1074. The value of Q in this case is 4978 1/K, which is close to the value of 5000 1/K recommended in ASTM C 1074 for concrete with Type I cement. The measured setting times can be converted to the equivalent setting times at 23 ºC by using Eq. (2). These values are shown as the open squares in Fig. 5(a). It is seen that the equivalent setting times are very close to the same value. Thus by measuring setting times at two extreme temperatures, it is possible to estimate the setting times for any temperature within the extremes.

Aside from demonstrating that setting times at different temperatures can be estimated on the basis of the maturity method, Pinto and Hover's work may lead to a simplified method for determining the apparent activation energy associated with strength gain. Measuring setting times at different temperatures is simpler than the procedure recommended in ASTM C 1074, which involves measuring strength development of mortar mixtures. This is worthy of additional study.

ASTM Practice C 1074

In 1987, ASTM adopted a standard practice on the use of the maturity method to estimate in-place strength [ASTM C 1074]. Application of the maturity method requires the following steps:

- Determination of the appropriate maturity function for the specific concrete that will be used in construction.
- Determination of the relationship between compressive strength and the maturity index.
- Measurement of the in-place maturity index and estimation of the in-place strength.

These steps are shown schematically in Fig. 6.

ASTM C 1074 permits the user to express the maturity index using either the temperature-time factor based on Eq. (1) or equivalent age based on Eq. (2). For the Nurse-Saul function, it is recommended that the datum temperature be taken as 0 °C if ASTM Type I cement is used without admixtures and the expected curing temperature is within 0 °C and 40 °C. For the Arrhenius equation, an activation energy of 41.5 kJ/mol is recommended. For other conditions or when maximum accuracy is desired, the best value of the datum temperature or activation energy should be determined experimentally.

The ASTM standard provides procedures for developing the strength-maturity relationship and for estimating the in-place strength. In addition, a procedure is provided for obtaining the datum temperature or activation energy, if that is desired.

Datum Temperature or Activation Energy**—**The procedure for determining the datum temperature or activation energy follows the approach discussed previously in the section "Effect of Temperature on Strength Gain." Basically, mortar cubes made with the materials to be used in construction are cured at three temperatures. Two of the curing temperatures should be the minimum and maximum curing temperatures expected for the in-place concrete, and the third temperature should be midway between the extremes. The cubes are tested for compressive strength at regular time intervals.

Alternative procedures are permitted for determining the rate constants under the three curing conditions. The simplest approach is to use statistical analysis software that allows least-squares fitting of Eq. (7). The strength-age data for each curing temperature are used to obtain the k value in Eq. (7). If the user does not have this capability, an alternative approach is to determine the final setting times at the three curing temperatures using the penetration resistance method [ASTM C 403/C 403M]. The final setting times are used to approximate the ages when strength development is assumed to begin, that is, t_0. For each curing temperature, the reciprocals of the cube strengths are plotted as a function of $1/(t-t_0)$. This approach makes use of a transformation of Eq. (7) that results in a linear equation between the inverse of strength and the inverse of age [Carino 1991]. For each temperature, the least-squares best-fit straight line is determined, and the rate constant is obtained by dividing the intercept by the slope of line.

To obtain the datum temperature, the rate constants are plotted as a function of temperature and the best-fit straight line is determined. The intercept of the line with the temperature axis is the datum temperature. To obtain the activation energy, the natural logarithms of the rate constants are plotted against the reciprocals of the absolute curing temperatures. The negative of the slope of the straight line equals the activation energy divided by the gas constant (referred to as Q in ASTM C 1074).

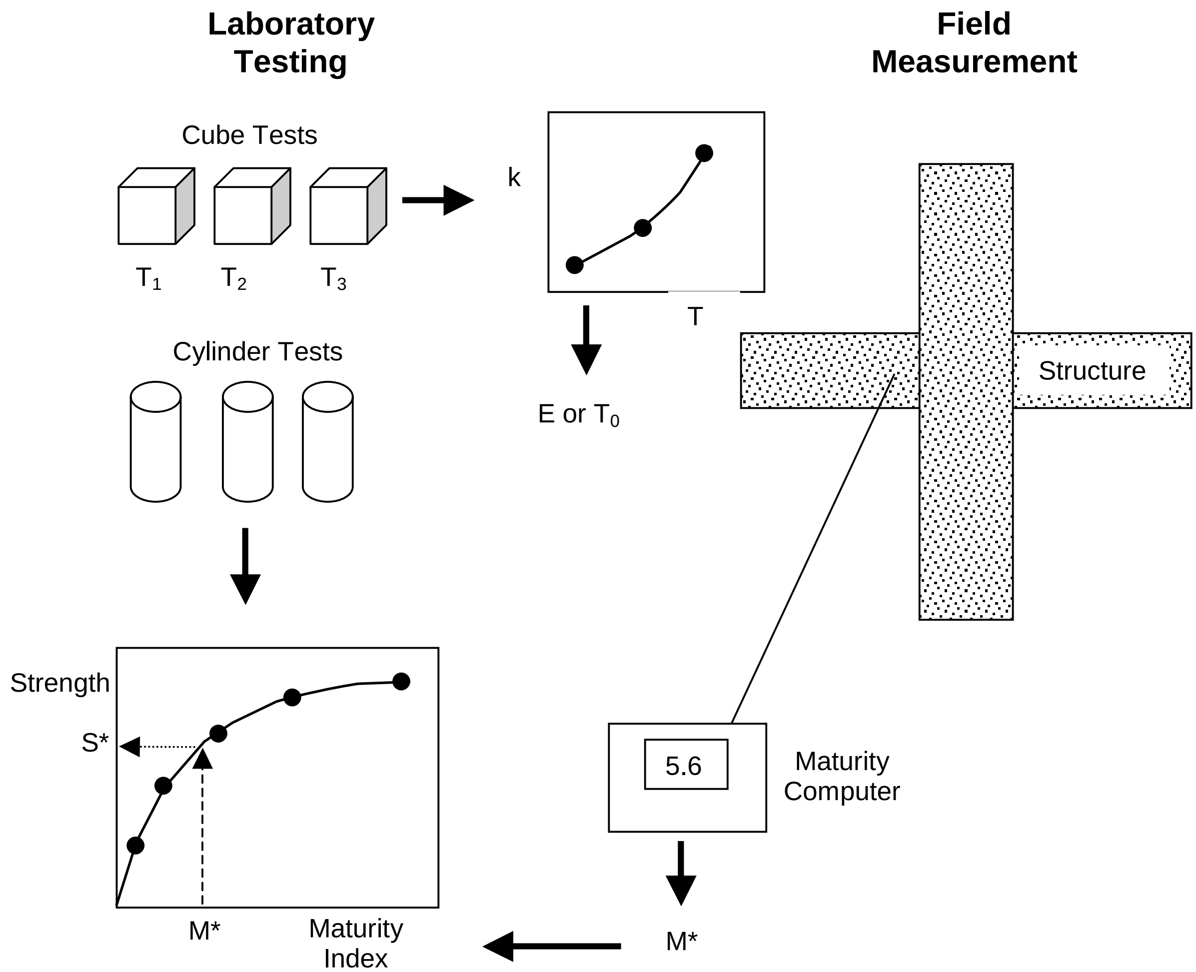

Fig. 6—Application of the maturity method requires laboratory testing and field measurement of temperature history

Strength-maturity Relationship—To develop the strength-maturity relationship, cylindrical concrete specimens are prepared using the mixture proportions and constituents of the concrete to be used in construction. These specimens are prepared according to the usual procedures for making and curing test specimens in the laboratory.

After the cylinders are molded, temperature sensors are embedded at the centers of at least two cylinders. The sensors are connected to instruments that automatically compute maturity or to temperature recording devices.

The specimens are cured in a water bath or in a moist curing room. At ages of 1, 3, 7, 14, and 28 days, compression tests are performed on at least two specimens. At the time of testing, the average maturity value for the instrumented specimens is recorded. If maturity instruments are used, the average of the displayed values is recorded. If temperature recorders are used, the maturity is evaluated according to Eq. (1) or Eq. (2). A recording time interval of one-half hour or less should be used for the first 48 hours, and longer time intervals are permitted for the remainder of the curing period.

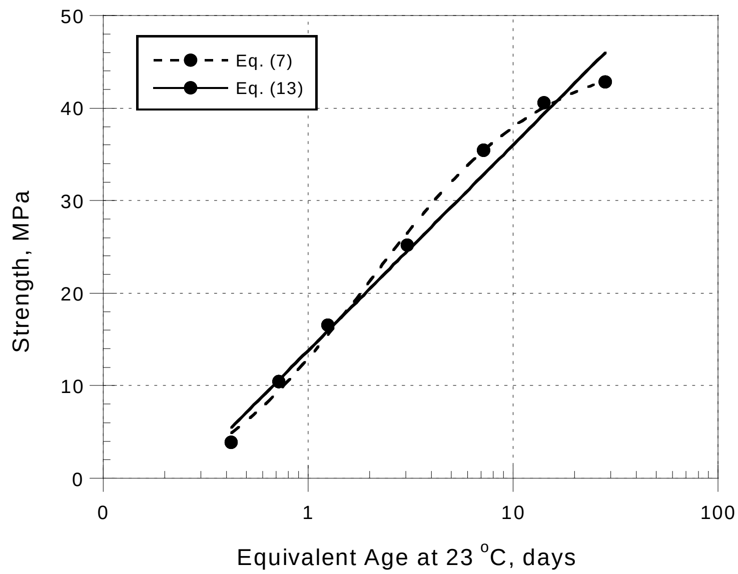

Fig. 7— Comparison of strength-maturity relationships; the logarithmic function, Eq. (13), does not fit the data as well as the linear hyperbolic function, Eq. (7).

A plot is made of the average compressive strength as a function of the average maturity index. A best-fit smooth curve is drawn through the data, or regression analysis may be used to determine the best-fit curve for an appropriate strength-maturity relationship. The resulting curve would be used to estimate the in-place strength of that concrete mixture.

One of the popular strength-maturity relationships is the following logarithmic equation proposed by Plowman (1956):

$$S = a + b\log(M) \tag{13}$$

where

- a = strength for maturity index M =1,
- b = slope of line, and
- M = maturity index

Equation (13) is popular because of its simplicity; it plots as a straight line when a log scale is used for the maturity index axis, but it has its limitations. It does not provide a good representation of the relationship between strength and maturity index for low or high values of the maturity index. It predicts that strength keeps on increasing with maturity index, that is, there is no limiting strength. In fact the slope of the line, *b*, represents the strength increase for every ten-fold increase in maturity index. Figure 6 illustrates that it may not be the most appropriate equation to use for the strength-maturity relationship. In this case, strength versus equivalent age data are fitted with Eq. (13) and the linear hyperbolic equation given by Eq. (7). It is clear that Eq. (13) does not represent the relationship between strength and maturity index over the range of values from about 0.4 d to 28 d shown in the Fig. 7.

The ASTM standard assumes that the initial temperature of the concrete in the field is approximately the same as the laboratory temperature when the cylinders were prepared. If the actual early-age temperatures are significantly greater than the laboratory temperatures, the limiting in-place strength is reduced. Thus the in-place strength may be over-estimated by the strength-maturity relationship.

***Estimating In-place Strength*—**The procedure for estimating the in-place strength requires measuring the in-place maturity. As soon as is practicable after concrete placement, temperature sensors are placed in the fresh concrete. The sensors should be installed at locations in the structure that are critical in terms of exposure conditions and structural requirements. The importance of this step cannot be over emphasized when the strength estimates are being used for timing the start of critical construction operations.

The sensors are connected to maturity instruments or temperature recording devices that are activated as soon as is practicable after concrete placement. When a strength estimate is desired, the maturity index from the maturity instrument is read or the maturity index is evaluated from the temperature record. Using the maturity values and the previously established strength-maturity relationship, compressive strengths at the locations of the sensors are estimated.

Because the temperature history is the only measurement made in the field, there is no assurance that the in-place concrete has the correct mixture proportions. Therefore, ASTM C 1074 requires verification of the potential strength of the in-place concrete before performing critical operations, such as formwork removal or post-tensioning. Failure to do this can lead to drastic consequences in the event of undetected batching errors, such as using excessive amounts of cement replacements or retarding admixtures. Alternative methods for verification of concrete strength include: (1) other in-place tests that measure an actual strength property of the in-place concrete; (2) early-age compressive strength tests of standard-cured specimens molded from samples of the concrete in the structure; or (3) compressive strength tests on specimens molded from samples of the concrete in the structure and subjected to accelerated curing. As was mentioned in the section “In-place Strength,” the maturity method can only provide information on relative strength gain.

Summary

This paper provides an introduction to the maturity method for estimating in-place strength development of concrete during construction. Proper application of this relatively simple procedure can result in savings by allowing construction operations to be performed safely at the earliest possible time. To assure safety, however, the user needs to understand the inherent approximations and limitations of the method. These are some of the authors’ ideas about the maturity method:

- The maturity function is related to the temperature sensitivity of initial strength development, and there is no single maturity function that is applicable to all concrete mixtures. The applicable maturity function for a given concrete can be obtained by measuring the variation of the rate constant with the curing temperature.
- The linear hyperbolic function, Eq. (7), is recommended for analyzing strength-age data to obtain the rate constants at different curing temperatures.
- Equation (5) can be used to represent the variation of the rate constant with curing temperature. The temperature sensitivity factor governs the rate at which the rate constant increases with temperature and is analogous to the “*activation energy*” in the Arrhenius equation.

- The equivalent age can be calculated from the temperature history using Eq. (6). This is simpler in form than Eq. (2) based on the Arrhenius equation.
- The logarithmic strength-maturity relationship, Eq. (13), needs to be used with caution because it may not be the best fit to strength versus maturity index data.
- The maturity method is more reliable in estimating relative strength development rather than absolute strength.
- Critical construction operations should not be initiated on the basis of maturity index values and the strength-maturity relationship without further verification that the in-place concrete has the expected strength potential.

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