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The Maturity Method: Theory and Application

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ABSTRACT: The maturity method may be used to predict the in-place strength of hardening concrete based on its thermal history. A theoretical basis for the maturity method is presented. The general form of the time-temperature function is found to be the time integral of the rate constant. For the case of linear dependence between temperature and the rate constant, the time-temperature function becomes the traditional maturity function. The Arrhenius equation is shown to be an accurate representation of the temperature dependence of the rate constant, and the concept of equivalent age is explained for practical application of the Arrhenius equation. It is explained how the accuracy of strength prediction by the traditional maturity method can be improved by using the proper datum temperature. Results illustrate that the appropriate value of apparent activation energy or datum temperature for concrete may be obtained from strength-gain data of isothermally cured mortar specimens.

KEYWORDS: activation energy, concretes, mortars (materials), strength, temperature, Arrhenius equation, equivalent age, maturity, nondestructive tests

Nomenclature

- A Constant used in representing the linear variation of the rate constant with temperature, $(°\text{C-day})^{-1}$
- B Constant used in the Arrhenius equation representing the variation of the rate constant with temperature, day^{-1}
- E Apparent activation energy, kJ/mol
- $F(t, T)$ Time-temperature function
- $f(S)$ Function of concrete strength affecting the rate of strength development, MPa
- $k(T)$ Function representing the variation of the rate constant with temperature, day^{-1}
- k_a Average value of rate constant during a time interval, day^{-1}
- k_s Value of the rate constant at a standard temperature, day^{-1}
- k_T Value of the rate constant at a specific temperature, day^{-1}
- M Maturity value at any age, °C-day
- M_o Maturity value at age t_o, °C-day
- M_{28} Maturity value at 28 days, °C-day
- R Gas constant, 8.3144 $\text{J}\cdot(\text{K-mol})^{-1}$
- S Compressive strength, MPa
- Su Limiting compressive strength at infinite age, MPa
- S_{28} Strength after 28 days at 23°C, MPa
- t Age, days
- t_e Equivalent age, days
- t_o Age when strength development is assumed to begin, days
- t_{req} Age required to reach a desired maturity, days
- T Temperature of cement, mortar, or concrete, °C
- T_a Cumulative average temperature of concrete, °C
- T_k Absolute temperature of cement mortar or concrete, K
- T_o Datum temperature used to calculate maturity, °C
- T_s Standard temperature, °C
- α S/S_{28}
- β S_u/S_{28}
- Δt Time interval, days
- γ Affinity ratio, the ratio of the rate constant at any temperature to its value at a standard temperature

In concrete construction, there is a growing interest in the use of methods to predict the in-place strength of concrete. A driving force is the economic benefit that can be derived by using accelerated construction schedules, but such acceleration requires means to monitor in-place strength so that structural safety can be maintained at all times. Bickley [*1*] has presented a specific example of high-rise construction where the use of accelerated scheduling and in-place testing resulted in significant economic savings without compromising safety.

There are available several methods for monitoring in-place strength, which have been incorporated into ASTM Test Methods [*2*]. These include the rebound number method (ASTM Test Method for Rebound Number of Hardened Concrete C 805), the penetration resistance method (ASTM Test Method for Penetration Resistance of Hardened Concrete [C 803]), the pullout strength method (ASTM Test Method for Pullout Strength of Hardened Concrete [C 900]), the cast in-place cylinder method (ASTM Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds [C 873]) and the field-cured cylinder method (ASTM Making and Curing Concrete Test Specimens in the Field [C 31]). All of the above have inherent limitations that should be considered when selecting a method to use and when interpreting the test results. There is however another method that may be used, which is not yet incorporated in an ASTM standard. This is the maturity method, and it is the subject of this paper.

As is well known, the strength of a given concrete mixture—properly placed, consolidated, and cured—will be a function of its age and temperature history. Around 1950, a series of articles appeared that proposed a method for accounting for the combined effects of time and temperature on strength development by using

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a single number [3-5]. Saul [5] termed this single factor, "maturity," and it was calculated according to the following expression

$$M = \int_{o}^{t} (T - T_o)dt \tag{1}$$

where

M = maturity at age t,
T = temperature of the concrete, and
T_o = datum temperature.

According to the "maturity concept," samples of the same concrete will have equal strength if they have equal maturity, irrespective of their actual time-temperature histories [5].

In Eq 1, the datum temperature T_o was taken to be the temperature below which there would be no further strength gain with time. In North American practice the accepted value of T_o is $-10°C$ [6].

Following the publication of the "maturity concept," there were reports of its validity [7,8]. However, there also were reports of cases in which the concept was found to be invalid [9-11]. Nevertheless, the concept has been viewed as a useful and simple means for accounting approximately for the complex effects of time and temperature on strength development. Malhotra carried out a comprehensive review of the subject until 1971 [12].

There have been proposed alternative time-temperature functions to that given by Eq 1 [13,14]. A function based on the Arrhenius equation was presented by Freiesleben Hansen and Pedersen [15], and it has found widespread acceptance in European practice [16-18]. In a comparative study of various time-temperature functions, Byfors [19] demonstrated that the function based on the Arrhenius equation was best able to account for the combined effects of these two variables on strength gain.

Currently ASTM Subcommittee C09.02.05 on Nondestructive Testing of Concrete is in the process of developing a standard for using the maturity method to predict the in-place strength of concrete, and this document has been prepared in order to assist the subcommittee in this task. This paper represents the latest effort in a long-term study of the maturity method carried out at the National Bureau of Standards (NBS) [20-25].

The objective of the paper is to provide a basis for in-place strength prediction of concrete using a time-temperature function, such as maturity. We begin with an analytical treatment of concrete strength gain in order to determine the general form of the time-temperature function. The fundamental approximation underlying the maturity method and the basis of the method using the Arrhenius equation are identified. The theoretical development is followed by test results to illustrate agreement of data with theory. Finally, a procedure is suggested for applying the knowledge in engineering practice.

Analytical Development

When Eq 1 was proposed as an approximate method to account for time and temperature effects, a theoretical basis was not given for why such a function could be used. Its applicability was based upon empirical evidence. In this section, the general form of the time-temperature function is derived, and it is shown that Eq 1 arises by assuming a specific type of behavior.

Strength Gain Function

We begin by considering the rate of compressive strength development of a given concrete mixture. As presented in 1956 by Bernhardt [26], the rate of strength gain dS/dt at any age t can be assumed to be a function of the current strength S and the temperature T

$$dS/dt = f(S) \cdot k(T) \tag{2}$$

where $f(S)$ is a function of strength, and $k(T)$ is a function of temperature. Based on empirical evidence, Bernhardt proposed that

$$f(S) = Su[1 - (S/Su)]^2 \tag{3}$$

where Su is the limiting strength at infinite age.

Assuming Su is independent of curing temperature and combining Eqs 2 and 3, we obtain

$$\int_{0}^{S} dS/[1 - (S/Su)]^2 = Su \int_{t_o}^{t} k(T)dt \tag{4}$$

Equation 4 is a departure from Bernhardt's derivation in that we have introduced the condition that strength equals zero not at zero age but at a later age t_o. This is used to approximate for the induction period between initial mixing and the start of strength gain as governed by Eq 2.

The integral on the right side of Eq 4 is the general form of the time-temperature function, which will be denoted as $F(t, T)$

$$F(t, T) = \int_{t_o}^{t} k(T)dt \tag{5}$$

After integrating the left side of Eq 4 and rearranging terms, we obtain the following general strength-gain function

$$S = Su\{F(t, T)/[1 + F(t, T)]\} \tag{6}$$

Isothermal Conditions—For the special case of constant concrete temperature, the general strength-age function reduces to a simple expression

$$S = Su\{[k_T(t - t_o)]/[1 + k_T(t - t_o)]\} \tag{7}$$

where k_T is the value of the temperature function, or the rate constant, at the concrete temprature T. A plot of Eq 7 is shown in Fig. 1*a*; the curve is a hyperbola with initial slope at t_o equal to $k_T Su$, and the curve is asymptotic to the limiting strength Su.

A similar hyperbolic curve, but without a t_o term, was proposed by Goral [27] and later recommended by Committee 209 of the American Concrete Institute (ACI) [28] for predicting compressive strength at any age. In the ACI report, different values for k_T are recommended for Type I and Type III portland cements.

A similar expression to Eq 7 was elegantly derived by Knudsen [29] using a different approach. He worked with the degree of hydration of cement rather than concrete strength, and he considered the reaction kinetics of the individual cement grains and the particle size distribution of the grains. The key assumptions in Knudsen's derivation are as follows:

- All cement particles are similar chemically and need be classified only according to their size.
- The cement particles react independently.
- The particle size distribution is described by an exponential equation.
- The kinetic equation for hydration of each particle is also described by an exponential equation.

Knudsen concludes that the hyperbolic equation given by Eq 7 holds not only for strength development but for any other property of concrete that is directly related to the extent of cement hydration. Two other conclusions [*29*] deserve mention. The hydration behavior of portland cement is rather insensitive to the specific details of the single-particle kinetic equation because "the broad particle-size distribution of portland cement blurs the kinetic details." In addition, the rate constant k_T depends upon the particle size distribution of the cement and the single-particle rate constant (which is temperature dependent). The importance of the particle-size distribution on the rate constant was also discussed by Bezjak and Jelenić [*30*]. Another interesting feature of the rate constant k_T in Eq 7 is that its inverse ($1/k_T$) equals the time beyond t_o needed for strength to reach 50% of the limiting strength [*29*].

The assumption, in Knudsen's derivation, that cement particles react independently is also significant. As is well known, hydration products form in the water-filled spaces between cement particles. As the *W/C* ratio is lowered the distance between cement particles is also reduced, and one would expect the hydration rate to be lowered. Thus, Knudsen points out that the assumption of particle independence would be expected to be violated at very low *W/C* ratios. However, Copeland and Kantro [*31*] point out that for a low *W/C* ratio, the effects of particle interference on hydration are not present at early ages. The significance of this discussion is that the rate constant k_T is independent of the *W/C* ratio at the early stages of hydration. Knudsen, based on his results, concluded that the assumption of independent particle reaction was not seriously violated at a *W/C* ratio as low as 0.4 [*29*].

Concerning the age t_o when strength gain is assumed to begin, Geiker and Knudsen [*32*], working with cement paste, found that t_o increased as the *W/C* ratio increased. Carino [*23*], on the other hand, found that for mortars t_o appeared to be independent of the *W/C* ratio. The different conclusions may be attributed to differences in the initial consistencies of the samples. In the NBS work, the mortar samples had similar initial consistency despite differences in their *W/C* ratios (this was achieved by using different aggregate contents).

In summary, the hyperbolic curve given by Eq 7 appears to be an accurate representation of the strength development of concrete under constant curing temperature.

Variable Temperature Conditions—We next consider strength development when the concrete temperature is not constant. In order to evaluate the time-temperature function, Eq 5, the rate constant has to be expressed as a function of temperature. First, we will consider the case of a linear variation

$$k(T) = A(T - T_o) \tag{8}$$

where

T_o = is the temperature corresponding to a zero rate constant and
A = a constant.

The time-temperature function can now be expressed as

$$F(T, t) = A \int_{t_o}^{t} (T - T_o)dt \tag{9}$$

Noting the similarity between Eq 9 and Eq 1, we see the fundamental assumption of the traditional maturity concept: the rate constant is taken to be a linear function of temperature.

Next we introduce maturity values as follows

$$M = \int_0^t (T - T_o)dt \tag{10a}$$

$$M_o = \int_0^{t_o} (T - T_o)dt \tag{10b}$$

where

M = maturity at age t and
M_o = maturity at age t_o.

The general strength-age function given by Eq 6 becomes the following

$$S = Su\{A(M - M_o)/[1 + A(M - M_o)]\} \tag{11}$$

Thus, under variable temperature conditions, the strength gain of concrete is a function of maturity. However, the accuracy of Eq 11 depends upon the accuracy of Eq 8 in representing the temperature dependence of the rate constant.

Until now, we have for simplicity assumed that the limiting strength *Su* is independent of curing temperature. However, it is widely known that this is not true. A higher curing temperature will lower the limiting strength. Further, it has been shown that it is the early age temperature that affects the limiting strength [*22,33-35*]. In reality there is therefore not a single strength-maturity function for a given concrete mixture, because different initial concrete temperatures will result in different values of *Su*. Nevertheless, it is proposed that there is a unique relative strength versus maturity function

$$S/Su = [A(M - M_o)]/[1 + A(M - M_o)] \tag{12}$$

Again, the accuracy of Eq 12 depends on the validity of Eq 8.

An alternative to assuming a linear relationship between the rate constant and temperature is to use the Arrhenius equation, whereby the time-temperature function becomes the following

$$F(t, T) = \int_{t_o}^{t} B \exp(-E/RT_k)dt \tag{13}$$

where

B = a constant,
E = apparent activation energy,
R = gas constant, and
T_k = absolute temperature in *K*.

As will be discussed subsequently, the Arrhenius equation is a better representation of $k(T)$ than the linear formula (Eq 8) when a wide variation is expected in the concrete temperature.

In summary, strength gain under conditions of varying temperature can be predicted by evaluating the time-temperature function at the desired age. The accuracy of the prediction will depend, in part, on the assumed relationship between the rate constant and temperature. It has been shown that a linear relationship results in the time-temperature function that has been classically referred to as "maturity."

As a practical matter, the evaluation of the time-temperature function can be approximated from the concrete temperature history in the following manner

$$F(t, T) \approx \sum_{t_o}^{t} k_a \cdot \Delta t \tag{14}$$

where k_a is the average value of the rate constant during the time interval Δt.

Equivalent Age Approach—An alternative to expressing strength gain in terms of the time-temperature function given by Eq 5 is to use the "equivalent age" approach first suggested in 1954 by Rastrup [*36*]. Equivalent age can be defined as the curing age at a constant standard temperature T_s that results in the same relative strength gain as under the actual temperature history. Mathematically, equivalent age t_e is defined as follows

$$t_e = \int_0^t [k(T)/k_s]dt \tag{15}$$

where k_s is the value of the rate constant at the standard temperature.

The ratio $k(T)/k_s$ has been termed the "affinity ratio" [*37*], and it transforms a time interval at any temperature to its equivalent, in terms of the effect on strength gain, at a standard temperature, that is

$$\Delta t_e = \gamma \Delta t \tag{16}$$

where

γ = the affinity ratio,
Δt = a time interval when the temperature equals T, and
Δt_e = the equivalent time interval at standard temperature T_s.

Using Eq 8, the affinity ratio is

$$\gamma = (T - T_o)/(T_s - T_o) \tag{17a}$$

and using the Arrhenius equation it is

$$\gamma = \exp[-E/R(1/T - 1/T_s)] \tag{17b}$$

In Eq 17b the temperatures T and T_s are in degrees Kelvin.

In summary, the equivalent age approach represents an alternative time-temperature function. Equivalent age is based upon the affinity ratio, which requires choosing a standard temperature T_s and knowing T_o or the apparent activation energy E—depending on which function is used—to represent the relationship between the rate constant and temperature.

In the next section, strength-age data under isothermal conditions are analyzed using the relationships developed above.

Experimental Results

In the previous section it was shown that the key element in using a time-temperature function is establishing the relationship between the rate constant and temperature. To illustrate how this can be done, we will use strength-age data for mortar cubes cured at constant temperatures of approximately 5, 12, 23, 32, and 43°C. The experimental procedure is given in Ref *23* and will not be reported here in detail. Basically, mortar mixtures were prepared in an environmental chamber at the above curing temperatures, and the molded cubes were stored in water baths maintained within ± 1°C of the nominal values. Three cubes were tested in compression at each of seven test ages, and the results are given in Table 1. Two *W/C* ratios were used, 0.43 and 0.56.

For each curing temperature, the strength-age data can be represented by Eq 7. The hyperbolic equation can be transformed into linear equations that will allow evaluation of the parameters *Su*,

TABLE 1—*Strength-age data for 2-in. mortar cubes.*[a]

W/C = 0.56				W/C = 0.43			
T, °C	t, days	S, psi	Coefficient of Variation, %	T, °C	t, days	S, psi	Coefficient of Variation, %
	1.32	115	9		1.29	315	19
	3.45	955	5		3.41	2260	5
	6.98	2065	4		6.94	4240	5
5.5	13.30	2890	4	5.5	13.27	6470	5
	27.04	4170	5		27.01	8160	6
	47.06	4880	3		47.01	9005	9
	67.14	5125	0		67.11	9360	6
	1.00	255	2		0.97	655	10
	2.08	985	18		2.04	2100	8
	4.54	1935	8		4.51	4035	4
12.5	9.00	2690	11		8.97	6310	5
	19.00	3160	4	13	18.97	7890	3
	31.96	3590	15		31.93	7890	7
	45.96	4335	9		45.93	9070	4
	0.51	250	21		0.48	435	4
	1.15	1060	20		1.11	1970	8
	2.40	1735	19		2.36	3700	2
23.0	5.04	2405	3	23.5	5.01	5840	5
	10.01	3340	16		9.97	7175	0
	21.00	3255	6		20.99	8285	3
	33.96	3570	15		33.92	8565	3
	0.41	325	6		0.38	630	11
	0.82	1030	3		0.79	2000	8
	1.82	2005	5		1.79	3920	3
32.0	4.14	2865	1	32.0	4.11	5850	1
	8.97	3385	4		8.94	6990	5
	16.00	3840	3		15.97	7620	3
	25.82	3905	3		25.79	7705	2
	0.26	305	9		0.22	450	12
	0.60	1270	6		0.56	2545	2
	1.42	2290	1		1.38	4565	2
43.0	3.17	3135	4	43.0	3.13	5995	3
	5.99	3490	5		5.95	6385	1
	12.99	3845	3		12.94	7425	8
	20.00	3990	3		19.96	7925	6

[a] inch-pound units were used since measurements were made in this system. 10 psi = 0.069 MPa. 1 in. = 25.4 mm.

k_T, and t_o using linear regression routines available on many handheld calculators.

First, we evaluate the limiting strength Su. Using the approach of Knudsen [29], we consider the data at later ages and make the approximation $t \approx (t - t_o)$. In this case Eq 7 can be rewritten as follows

$$1/S = 1/Su + (1/k_T Su)(1/t) \quad (18)$$

Thus, a plot of $1/S$ versus $1/t$ is a straight line, and the inverse of the intercept is the limiting strength (Fig. 1*b*).

The results of these regression analyses are given in Table 2. The values of n represent the number of data points—working from the latest to the earliest ages—that were used in estimating Su. The criterion was to use the number of points that produced the lowest estimated standard error in the intercept ($1/Su$), and this explains why the n-values differed.

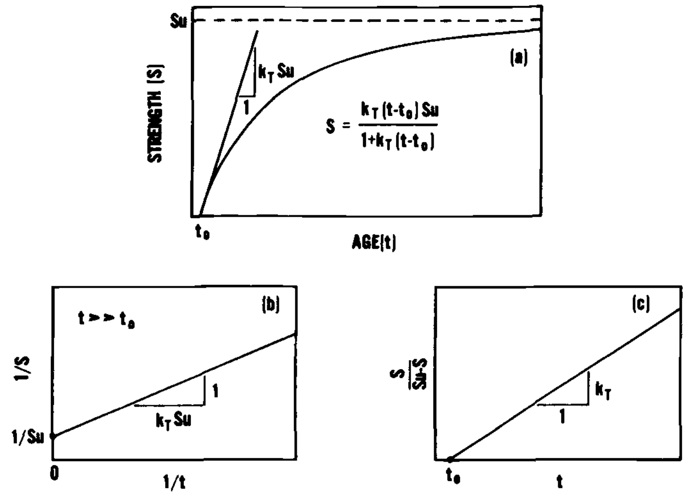

FIG. 1—*Strength-age function of isothermally cured concrete:* (a) *hyperbolic curve.* (b) *and* (c) *linear transformations.*

TABLE 2—*Analysis of strength-age mortar data to determine limiting strength.*[a]

T, °C	n	$1/Su$, $\times 10^{-6}$ psi^{-1}	Estimated Standard Error, $\times 10^{-6}$ psi^{-1}	Su, psi
		w/c = 0.43		
5.5	3	95.9	0.5	10430
13.0	4	104.4	6.3	9580
23.5	4	106.8	0.9	9370
32.0	4	119.9	1.8	8340
43.0	5	125.9	4.3	7940
		w/c = 0.56		
5.5	3	162.8	2.9	6140
12.5	5	226.9	13.4	4410
23.0	6	250.6	10.6	3990
32.0	5	235.6	3.4	4240
43.0	3	236.0	0.7	4240

[a] 10 psi = 0.069 MPa.

Having estimated the values of Su, Eq 7 can be written in following form to estimate k_T and t_o

$$S/(Su - S) = -k_T t_o + k_T t \quad (19)$$

Thus, a plot of $S/(Su - S)$ versus t is a straight line having a slope k_T and a t-axis intercept of t_o (Fig. 1*c*). Table 3 gives the results of this second series of regression analyses. In this case the data points used were those from the earliest to later ages, and the number was based on the lowest standard error for the estimate of k_T.

We can now examine the variation of the rate constant with temperature. Figure 2*a* shows the estimated values of k_T (Table 3) as a function of the concrete temperature. Two things are evident: (1) the values of k_T appear to be independent of the W/C ratio and (2) over the range 5 to 43°C the relationship between k_T and temperature is clearly nonlinear. The first observation is consistent with Knudsen's findings [29]. The second observation shows that Eq 8, a linear equation, is not the best function to use for $k(T)$ over this wide temperature range.

Next, we consider the applicability of expressing $k(T)$ by the Arrhenius equation, as follows

$$k(T) = B \exp(-E/RT_k) \quad (20a)$$

Taking the natural logarithm of both sides of Eq 20a, we obtain

$$\ell n\, k(T) = \ell n\, B - (E/R)(1/T_k) \quad (20b)$$

Thus, if the rate constant obeys the Arrhenius equation, there should be a linear relationship between $\ell n\, k(T)$ and the reciprocal of the absolute temperatures.[2]

In Fig. 2*b*, we see that this condition is met to a reasonable degree. The best-fit equation is

$$\ell n\, k(T) = 16.52 - (5219/T_k) \quad (21)$$

and in Fig. 2*a* the exponential form of this equation is plotted. It is clear that the Arrhenius equation is a good representation of $k(T)$ over the temperature range 5 to 43°C.

TABLE 3—*Analysis of strength-age mortar data to determine rate constant.*

T, °C	n	$k_T t_o$	Estimated Standard Error	k_T, day^{-1}	Estimated Standard Error, day^{-1}	t_o, day
			w/c = 0.43			
5.5	3	0.118	0.0005	0.116	0.0001	1.02
13.0	3	0.101	0.0090	0.184	0.0031	0.55
23.5	5	0.114	0.0277	0.341	0.0054	0.33
32.0	3	0.136	0.0010	0.571	0.0008	0.24
43.0	4	0.121	0.0406	1.031	0.0234	0.12
			w/c = 0.56			
5.5	3	0.103	0.0170	0.087	0.0037	1.19
12.5	3	0.139	0.0064	0.203	0.0022	0.68
23.0	4	0.033	0.0525	0.313	0.0184	0.10
32.0	3	0.153	0.0012	0.577	0.0010	0.27
43.0	4	0.157	0.0130	0.944	0.0073	0.17

[2] $K \simeq$ °C + 273.

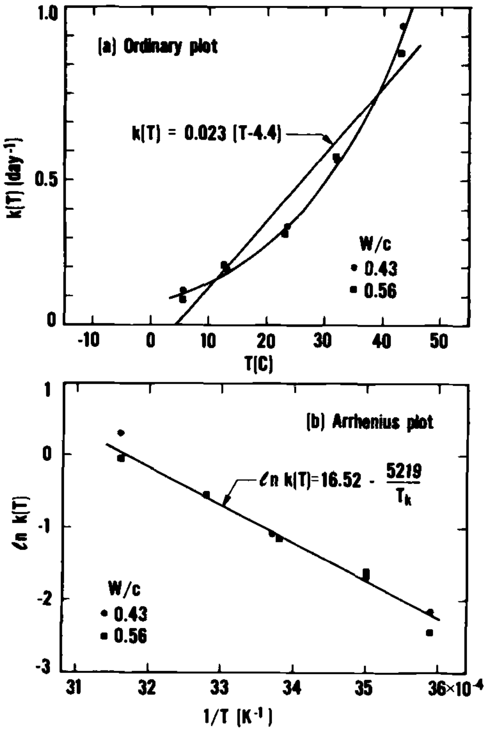

FIG. 2—*Rate constant versus curing temperature for mortar cube specimens.*

Also plotted in Fig. 2*b* is the following best-fit linear equation for $k(T)$

$$k(T) = 0.023\,(T - 4.4°\text{C}) \tag{22}$$

This is a highly significant result. It shows that the generally accepted value of $-10°$C for the datum temperature T_0 would not in this case produce the best representation of $k(T)$. Thus, if we are to continue using the traditional maturity method, we can improve the accuracy of in-place strength prediction by using the value of T_0 that results in the best estimate of the true $k(T)$ function.

Activation Energy Versus Datum Temperature

At this point it is appropriate to discuss relationships between the datum temperature T_0 and apparent activation energy E.[3] The datum temperature is the key aspect of the traditional maturity method adopted in North American practice [*6*], and activation energy is the key feature of the equivalent age approach adopted in most European practices [*16,17,18*]. The simplest approach is to consider the affinity ratio as defined by Eqs 17*a* and 17*b*. In Fig. 3, the solid lines represent the affinity ratio variations using Eq 17*b*, with a standard temperature of 20°C (293 K) and for a low value (30 kJ/mol) and a high value (56 kJ/mol) of activation energy. The plotted values are taken from Ref *16*.

[3] Hydration is not a simple single-phase reaction, and homogeneous reaction kinetics do not apply strictly [*41*]. This is the reason the term "apparent" has been used, but for simplicity the remainder of the paper will refer to "activation energy."

In Fig. 3, we see the effect of activation energy on the rate constant. As the activation energy increases, the rate constant becomes more temperature sensitive, and the variation with temperature becomes more nonlinear. Suppose the two curves in Fig. 3 are to be approximated by straight lines, then it is necessary to find the values of T_0 that produce the best-fit lines to the nonlinear curves. These lines must pass through the point (1, 20°C). To improve the linear approximations, we shall use two line segments to represent each curve: one segment for the temperature range 0 to 20°C and the other segment for the range 20 to 40°C. These straight-line approximations are shown in Fig. 3. It is seen that for low activation energy, the straight lines are reasonable approximations of the nonlinear curve. Whereas for high activation energy, the straight lines are crude approximations of the nonlinear curve. This is a significant observation, for it indicates that the traditional maturity method (based upon Eq 8) will be inherently less accurate for concrete mixtures having high activation energies.

Similar straight-line approximations of the affinity-ratio curves were determined for other values of activation energy using the tabulated values in Ref *16*. The results are summarized in Fig. 4, which shows the best values of the datum temperature as a function of the activation energy and the temperature range. The range 0 to 20°C could be representative of cold weather concreting, and the range 20 to 40°C could be representative of hot weather concreting.

The purpose of the above exercise is to illustrate that if we are to continue using the traditional maturity method, the value of the datum temperature should be chosen so that it results in the best straight-line approximation of the $k(T)$ function. It is felt that the mathematical simplicity of the traditional maturity method makes it more attractive than the equivalent age approach based upon the

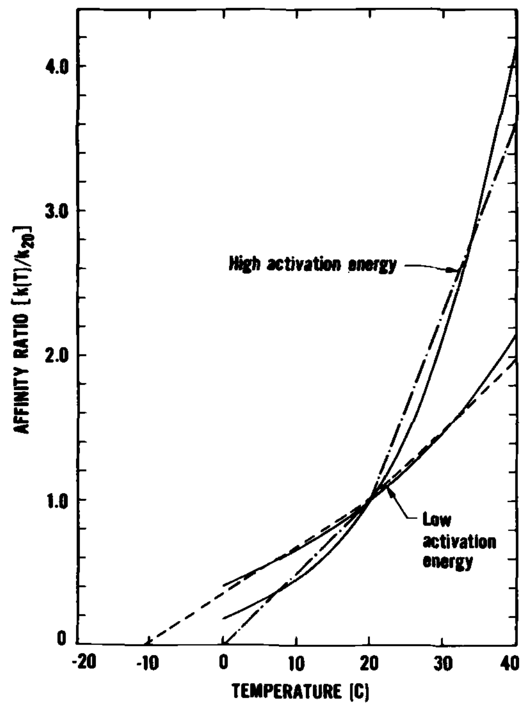

FIG. 3—*Affinity ratio versus curing temperature, showing linear approximations for two values of activation energy and two temperature ranges.*

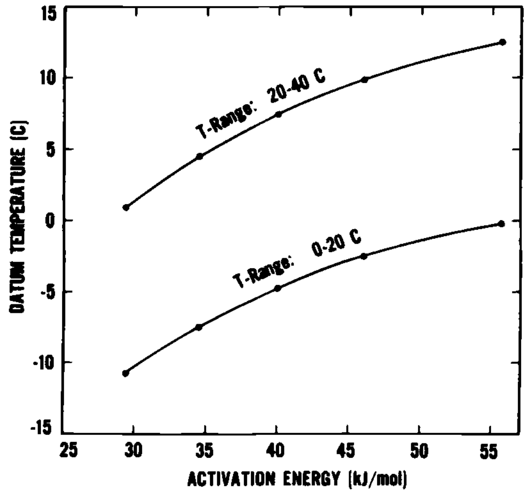

FIG. 4—*Approximate relationships between activation energy and datum temperature for curing temperature ranges 0 to 20°C and 20 to 40°C.*

Arrhenius equation. The information given in Fig. 4 enables one to use the traditional maturity method and still attain strength predictions with accuracy comparable to using the Arrhenius function. Note that a datum temperature of −10°C is appropriate only for the case of low activation energy and 0 to 20°C temperature range.

Activation Energy Values

In using a time-temperature function, one must know the activation energy for the rate constant of the concrete mixture. The question is: How can the activation energy be determined? One approach might be to make and cure concrete specimens at several different temperatures and use regression analysis to analyze the strength-age data. However, there are alternative possibilities. It has been firmly established that the degree of hydration of cement correlates with the mechanical strength of concrete [*38,39*]. Thus, it is possible to determine activation energy from hydration studies of cement pastes. This approach is supported by the work of others [*17,37*] who have shown that the activation energies based upon heats of hydration are the same as those based upon the mechanical strength of mortars. In addition, Bresson [*16*] and Gauthier and Regourd [*17*] report that the same value of activation energy is obtained from strength tests of mortar specimens as with concrete specimens. Thus, it appears that the activation energy of the rate constant can be determined without testing bulky concrete specimens.

Presently there is not much published data on the activation energy of different cements. As such data are accumulated, it may be possible to predict the activation energy of a particular cement based upon its chemical composition. When admixtures are used, their effects on the activation energy must also be determined. This can probably only be done by testing the combinations of cement and admixtures that will be used.

For cases where the accuracy of strength predictions is not crucial, typical published values of activation energy can be used. Gauthier and Regourd [*17*] report that for ordinary portland cement the activation energy is typically between 42 and 47 kJ/mol, and they have reported a value of 56 kJ/mol for a blended cement with 70% blast furnace slag. Other published data appear to confirm the above range for portland cement [*40,41*]. For the mortar tests that resulted in Fig. 2, the calculated activation energy is 43.4 kJ/mol.

On the other hand, Freiesleben Hansen and Pedersen [*15*] suggested using an activation energy of 33.5 kJ/mol for temperatures above 20°C, and increasing the value 1.47 kJ/mol for every 1°C below 20°C, so that at 0°C it would be 64.4 kJ/mol. No explanation was given for how these values were obtained.

Bresson [*16*] suggests that the activation energy can be obtained based upon the 2-day strength of cement paste. Unfortunately, the article does not give sufficient detail of the procedure to use.

In summary, this section of the paper has dealt with the variation of the rate constant with curing temperature, which is the key element of the time-temperature function. It has been shown that for a wide temperature range the relationship $k(T)$ is nonlinear, and the relationship can be described by the Arrhenius equation. This means that the classical maturity function has inherent limitations in its ability to account for the combined effects of time and temperature on strength development. The value of activation energy effects the temperature sensitivity of the rate constant, and this value must be known in order to construct an accurate time-temperature function. Alternative methods have been discussed to determine the value of activation energy, and typical values have been given. The mathematical simplicity of the maturity method makes it attractive for practical application, and it has been shown how the activation energy affects the best value to use for the datum temperature in computing maturity values.

The following section discusses the application of mortar tests to establish the activation energy and datum temperature of a concrete mixture.

Application

In the previous section it was proposed that the time-temperature function of a concrete mixture could be established by testing mortar specimens. This is an attractive approach because it simplifies the testing program. In this section we compare the variations of the rate constant with curing temperature obtained from testing mortar specimens and from testing concrete specimens.

Experimental Procedure

In order to evaluate $k(T)$, specimens were cured at three temperatures, 12, 21, and 32°C. Unlike the previous mortar tests, the specimens were fabricated under ambient laboratory conditions, and the molded specimens were placed carefully into water baths maintained at the desired curing temperature. This was done within 1 h from initial mixing.

Concrete and mortar mixtures were proportioned with a *W/C* ratio of 0.55. For the concrete, the coarse aggregate was a rounded river gravel with 19-mm nominal maximum size, and the fine aggregate was a natural sand. The approximate percentages of absolute volumes were as follows: cement (Type I), 11%; water, 19%; coarse aggregate, 40%; fine aggregate, 28%; and the air content was assumed to be 2%. The mortar mixture had a fine aggregate to cement ratio of 3.0 (mass basis).

For the concrete, cylindrical specimens were molded using 102-by 203-mm (4- by 8-in.) plastic molds. The molds were filled in two layers, tamping each layer 15 times with a 10-mm diameter steel rod. For the mortar, cubic specimens were molded using 51- by 51- by 51-mm (2- by 2- by 2-in.) steel molds. The molds were filled in two layers, and each layer was tamped 15 times with a hard-rubber tamper. After molding, the concrete and mortar specimens were lowered into lime-saturated water baths and allowed to cure. The mortar cubes were all demolded at the time of the first strength test, but the concrete cylinders were kept in their molds until the time of testing.

To monitor the concrete temperatures, thermocouples were placed within two cubes and within two cylinders. Temperatures were monitored at 2-min intervals and the hourly average values were printed by a data logger. Based on the temperature data, it was found that the concrete specimens reached the nominal curing temperatures within 3 h after the start of mixing.

Three cubes and three cylinders were tested in compression at six different ages. In order to simplify testing, the cylinders were tested without capping compound. Instead they were tested using 13-mm thick neoprene pads, which were restrained by 109-mm steel rings welded to 13-mm thick steel plates. The neoprene was soft with a durometer hardness value of 50. Work by the Virginia Highway and Transportation Research Council [42] has shown that the compressive strength of 15- by 305-mm (6- by 12-in.) cylinders is not affected significantly by using neoprene pads restrained by steel rings.

TABLE 4—*Strength-age data for concrete and mortar specimens.*[a]

Concrete				Mortar			
T, °C	t, days	S, psi	Coefficient of Variation, %	T, °C	t, days	S, psi	Coefficient of Variation, %
	0.92	705	4		0.91	695	6
	1.83	1935	6		1.81	1650	1
12	5.45	3710	2	12	5.44	3115	1
	12.07	4720	2		12.06	3895	1
	25.97	5390	1		25.96	4745	1
	46.02	6075	1		46.01	5365	2
	0.51	510	4		0.49	700	1
	1.02	1680	2		1.01	1545	2
21	3.01	3075	1	21	2.99	2885	2
	7.00	4210	2		6.99	3820	4
	13.20	4990	1		13.19	4415	2
	28.00	5490	2		28.05	5260	2
	0.37	980	4		0.35	1080	2
	0.79	1925	3		0.75	1955	2
32	1.90	3040	1	32	1.87	3065	2
	5.00	4045	3		4.97	4320	2
	10.00	4530	3		9.97	4840	3
	20.76	4770	2		20.75	5170	2

[a] 10 psi = 0.069 MPa.

Results

The results of the compressive strength tests are summarized in Table 4. Figure 5 shows the average strength versus age data for the concrete cylinders. The data in Table 4 were subjected to regression analyses, as described in the previous section for the mortar tests, in order to determine the limiting strength Su and the rate constant k_T for each data group. The results of these analyses are summarized in Table 5 where n_1 is the number of data points (from the latest to the earliest ages) used to estimate Su, and n_2 is the number of data points (from the earliest to the latest ages) used to estimate k_T.

We now examine the variation of the value of the rate constant with temperature for the mortar and the concrete tests. The k_T values in Table 5 are plotted versus curing temperature in Fig. 6*a*. In Fig. 6*b* the natural logarithms of k_T are plotted versus the reciprocal of absolute temperature. The best-fit linear $k(T)$ function and the best-fit Arrhenius equation for $k(T)$ were determined. From

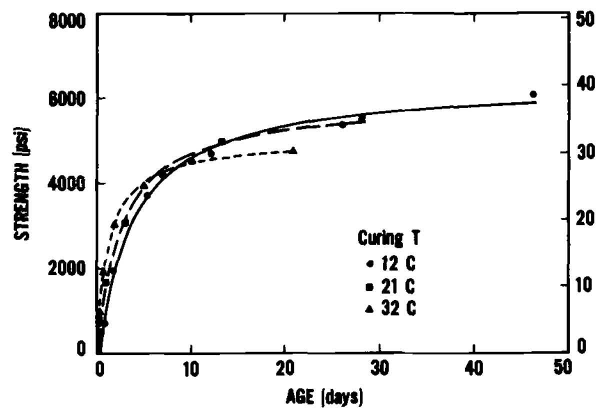

FIG. 5—*Strength versus age for isothermally cured concrete cylinders.*

TABLE 5—*Summary of results of regression analyses of the concrete and mortar data.*[a]

T, °C	n_1	$1/Su$, $\times10^{-6}$ psi^{-1}	Estimated Standard Error, $\times10^{-6}$ psi^{-1}	Su, psi	n_2	k_T, day^{-1}	Estimated Standard Error, day^{-1}
			CONCRETE				
12	5	154.5	3.3	6470	3	0.265	0.014
21	4	165.1	2.4	6060	3	0.361	0.042
32	5	197.0	2.6	5080	3	0.815	0.009
			MORTAR				
12	3	163.3	5.0	6120	3	0.196	0.014
21	4	180.5	7.1	5540	3	0.370	0.019
32	3	181.6	1.0	5510	3	0.657	0.028

[a] 10 psi = 0.069 MPa.

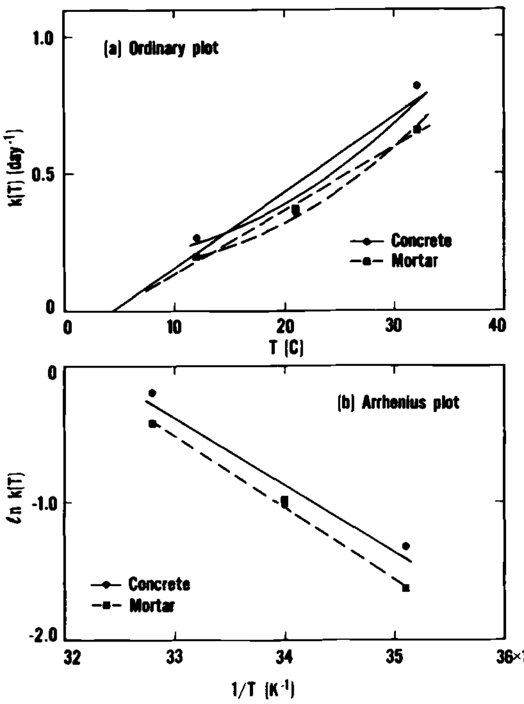

FIG. 6—*Comparison of rate constants of mortar and concrete specimens.*

these analyses the following values were obtained for the datum temperature T_o and the activation energy E:

T_o = 4.5°C, concrete,
T_o = 4°C, mortar,
E = 40.8 kJ/mol, concrete, and
E = 43.7 kJ/mol, mortar.

The above results appear to confirm the notion that tests of mortar cubes can provide the datum temperature or activation energy required to develop the time-temperature function of the concrete. While these values of activation energy are not precisely equal, there is no statistically significant difference when one considers the scatter about the regression lines of the concrete k_T values. It must be emphasized that the computed values of the datum temperature are applicable only over the temperature range 12 to 32°C.

We can now plot the concrete strength data in Table 4 in terms of a time-temperature function. The traditional maturity function is used with a datum temperature of 4°C. In addition, the strength values for each curing temperature are divided by the corresponding limiting strengths given in Table 5. The resulting relative strength versus maturity plot is presented in Fig. 7. The best-fit hyperbolic curve was obtained by rewriting Eq 12 in the following form

$$(S/Su)/[1 - (S/Su)] = -AM_o + AM \tag{23}$$

The values of A and M_o were obtained from linear regression using all 18 data points. From Fig. 7, it is seen that using the datum temperature obtained from the mortar tests produces a maturity function that can be used to describe the relative strength gain of the concrete cylinders.

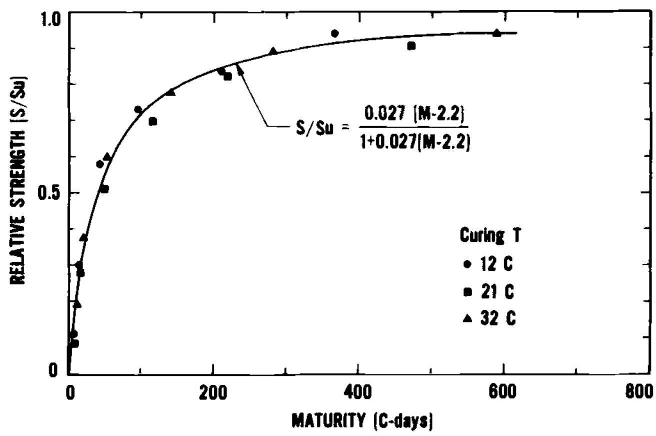

FIG. 7—*Relative strength versus maturity for isothermally cured concrete specimens using datum temperature of 4°C.*

Alternatively, the relative strength can be plotted versus the equivalent age at a standard temperature. Using an activation energy of 43.7 kJ/mol, the test ages in Table 5 were expressed as equivalent ages at 20°C by using Eq 17*b* to calculate the affinity ratios. In this calculation, it was assumed that the concrete temperatures were equal to the curing temperatures from zero age onward. The resulting relative strength versus equivalent age plot is presented in Fig. 8. The best-fit hyperbolic curve was obtained from regression analysis using an equation analogous to Eq 23 except that equivalent age values were used in place of maturity values. It is seen that using the activation energy value based upon the mortar tests also results in good representation of relative strength gain for the concrete.

In summary, the results appear to confirm the idea that tests of mortar specimens cured isothermally at different temperatures can provide the necessary information needed to describe the time-temperature function of concrete. Because curing temperature affects the limiting strength, the data have been presented in terms of relative strength, and the results presented in Figs. 7 and 8 show that the shape of the relative strength versus the time-temperature function (maturity or equivalent age) is independent of the curing temperature. In addition, it has been shown that by using the correct datum temperature, the traditional maturity function can describe relative strength gain almost as precisely as equivalent age based upon the Arrhenius equation.

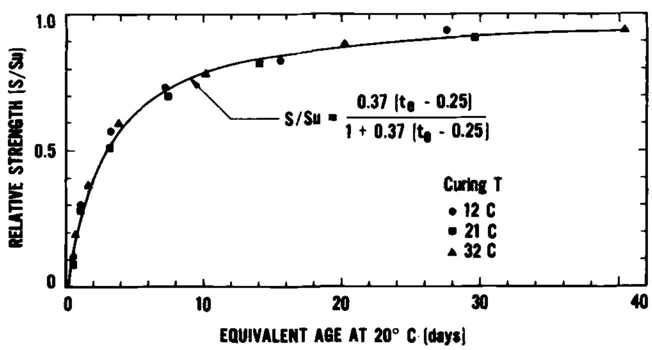

FIG. 8—*Relative strength versus equivalent age at 20°C for isothermally cured concrete specimens using activation energy of 43.7 kJ/mol.*

Summary and Discussion

This paper attempts to explain the theoretical basis of the maturity method, taking into account recent research on the subject. In so doing, the fundamental difference has been uncovered between the traditional maturity method and the equivalent age approach based upon the Arrhenius equation. A procedure has been proposed for improving the accuracy of in-place concrete strength prediction by the traditional maturity method.

In the theoretical development, it was shown that under isothermal conditions the strength gain of concrete can be described by a hyperbolic curve. The curve is defined by three parameters: (1) the age when strength development is assumed to begin t_o, (2) a rate constant k_T, which is related to the initial slope of the curve, and (3) the limiting strength Su. It has been shown that these parameters can be estimated from strength tests by transforming the data and using linear regression analyses. It has been further shown that the parameters are temperature dependent.

In order to describe strength gain under variable temperature conditions it is necessary to use a time-temperature function that accounts for the effect of these two factors. It has been shown that the product of the rate constant and age is the general form of the time-temperature function. Thus, the key element is to determine how the rate constant is affected by curing temperature.[4]

Test data have shown that over a wide temperature range, the rate constant is a nonlinear function of temperature. If we choose to approximate the rate constant versus temperature function $k(T)$ by a straight line, the resulting time-temperature function is identical to that of the traditional maturity method. The key parameter in this approach is the datum temperature T_o, and it has been shown that the traditional value of $-10°C$ is not necessarily the best value of this parameter.

The Arrhenius equation describes accurately the relationship between the rate constant and curing temperature. In this case, the key parameter is the activation energy, which defines the temperature sensitivity of the rate constant. The equivalent age method has been adopted in some countries as the practical approach for using the Arrhenius equation.

The mathematical simplicity of the maturity method makes it an attractive approach for field application, and by using the appropriate datum temperature its accuracy is comparable to the equivalent age method (based upon the Arrhenius equation). Figure 4 was developed to illustrate that the appropriate datum temperature depends on activation energy and curing temperature range.

Whether one chooses to use the equivalent age method or the maturity method to predict in-place concrete strength, the appropriate value of activation energy or datum temperature must be known for the concrete mixture. These values probably depend on the cement chemistry, the cement fineness, and the type and quantity of admixtures. Limited test results indicate that these values are not influenced by W/C ratio, except possibly for very low ratios. For concretes made with ordinary portland cement and without admixtures, it appears that the activation energy is between 40 and 45 kJ/mol. Using Fig. 4, the appropriate values of the datum temperature would be about $-4°C$ for cold weather conditions (0 to 20°C) and about 9°C for hot weather conditions (20 to 40°C).

For concretes made with other than ordinary portland cement or with admixtures that influence hydration or both, the activation energy or datum temperature must be experimentally determined. However, the actual concrete mixture does not have to be tested. The required information can be obtained by monitoring the heat of hydration of cement paste, with the intended admixtures, using a conduction calorimeter, or the information can be obtained from the compressive strength development of mortar cubes. In either case, it is recommended that testing be performed at three temperatures, which include the extreme temperatures expected in the in-place concrete. The procedures described in the "Experimental Results" section of this paper illustrate how the results of the isothermal curing tests can be used to determine the appropriate value of activation energy or datum temperature. As the maturity or equivalent age methods become more widely used, cement producers may wish to provide their users with values of datum temperatures or activation energies for their particular cements.

The strength versus equivalent age or the strength versus maturity function of the concrete can then be developed by testing concrete specimens cured at a constant temperature. The limiting concrete strength Su under the chosen curing temperature can be determined as previously discussed, and the curve of relative strength versus equivalent age or versus maturity can be established. This relative strength curve is applicable for all W/C ratios (expect probably less than 0.4) and for all curing temperatures within the range used to determine activation energy or datum temperature.

In order to use the relative strength versus equivalent age or versus maturity curve to estimate the absolute value of in-place strength, it is necessary to know the thermal history and the W/C ratio of the in-place concrete. The thermal history is required for two reasons. First, it gives the in-place value of equivalent age or maturity. In addition, the early age temperature of the concrete affects its limiting strength Su. Presently, there are no guidelines for predicting quantitatively the reduction in Su with increasing early age temperature. Some research indicates that the effect becomes more pronounced with increasing tricalcium aluminate content of portland cement [*43,44*]. However, the effect of early age temperature on limiting strength needs to be considered only when concrete is placed at a high initial temperature. The value of the W/C ratio is needed because of its obvious influence on the limiting strength. In practice, it must be verified that the design value of the W/C ratio has not been surpassed. The simplest approach is to apply careful quality control during all phases of concrete production.

The above approach using a relative strength versus equivalent age or versus maturity curve is an improvement over the traditional approach using absolute strength. Because of the early age temperature effect limiting strength, there is not a unique strength-equivalent age or strength-maturity function for concrete made of the same cement. However, there is a unique relative strength versus equivalent age or versus maturity curve. Relative strength gain is the only quantity that can be predicted solely from the time-temperature history. To predict absolute strength requires knowledge of additional factors.

Up to now relative strength has referred to the fraction of the limiting strength Su, which would be obtained after a curing period on the order of several years. In practice, the 28-day standard-cured strength has more meaning, and it is possible to express relative strength in terms of this quantity. For example, given the relative-strength versus maturity curve in Fig. 7, the relative strength for 28 days at 23°C would be 0.93.[5] Therefore, by dividing

[4] As used in this discussion curing temperature means the temperature of the concrete.

[5] The datum temperature in this case is 4°C, and the maturity value for 28 days at 23°C would be $(23 - 4) \times 28 = 532$°C-day.

the abscissa values of Fig. 7 by 0.93, relative strength would be in terms of the standard-cured 28-day strength. In the Appendix an application of this procedure for form removal is given.

An objective of this study was to determine whether or not compressive strength versus age data of isothermally cured mortar cubes could be used to determine the value of datum temperature or activation energy of concrete made with the same cement. The results presented in the previous section appear to confirm that this can be done. The mortar tests resulted in a datum temperature of 4°C and Fig. 7 shows relative strength versus maturity for the concrete tests using $T_o = 4°C$.

It is interesting to see how Fig. 7 would be altered if maturity were based on the traditional datum temperature of −10°C. This can be easily done by converting the maturity values using the following general expression

$$M_2 = M_1 + [(T_o)_1 - (T_o)_2]t \tag{24}$$

where

M_2 = maturity value for the datum temperature $(T_o)_2$,
M_1 = maturity value for the datum temperature $(T_o)_1$, and
t = age.

In this case $(T_o)_1 = 4°C$ and $(T_o)_2 = -10°C$. Figure 9 shows the relative strength values versus maturity based on the traditional datum temperature. Comparing Figs. 7 and 9, we see that using $T_o = -10°C$ results in more scatter of the relative strength values about the best-fit curve. This is a clear illustration of why it is necessary to use the appropriate datum temperature in order to increase the accuracy of strength prediction with the maturity method.

Commercially available maturity meters, which perform the calculation given by Eq 10*a*, employing a datum temperature of −10°C, can be used for other datum temperatures by correcting the displayed maturity according to Eq 24. In this case M_1 would be the displayed value, and M_2 would be the corrected value. Meters are also available that compute equivalent age using the Arrhenius equation. The users of the meters should be aware of the value of activation energy that is incorporated into the device, and they must realize that the displayed values of equivalent age will not be representative of the concrete when the actual activation energy is significantly different from that assumed by the device. It is hoped that the next generation of such meters will permit the user to select the value of datum temperature or activation energy.

Conclusions

1. Under isothermal curing conditions, the strength gain of concrete can be described by a hyperbolic curve having three parameters: (1) the limiting long-term strength Su, (2) the rate constant k_T, and (3) the age t_o when rapid strength development is assumed to begin. The parameters are temperature dependent.

2. Under variable temperature curing conditions, strength gain can be described using a time-temperature function whose general form is the time integral of the rate constant.

3. If the rate constant is assumed to be a linear function of the curing temperature, the time-temperature function becomes the traditional maturity function.

4. The Arrhenius equation appears to be a good representation of the variation of the rate constant with temperature over the temperature range encountered in ordinary concrete construction. A high value of the activation energy implies a high-temperature sensitivity of the rate constant. In addition, the variation of the rate constant with curing temperatures becomes more nonlinear as the activation energy increases.

5. Equivalent age or maturity can be used to estimate the level of relative strength gain of in-place concrete. To estimate the obsolute strength requires additional knowledge about the expected limiting strength of the in-place concrete.

6. The accuracy of predicted relative strength is improved by using the proper value of activation energy or datum temperature in calculating the in-place equivalent age or maturity.

7. The traditional datum temperature of −10°C currently used with the maturity method is not necessarily the best value to use.

8. The activation energy or datum temperature for concrete can be obtained from the strength-gain data of mortar specimens cured isothermally. It is suggested that three curing temperatures be used that span the range of expected in-place temperatures for the concrete.

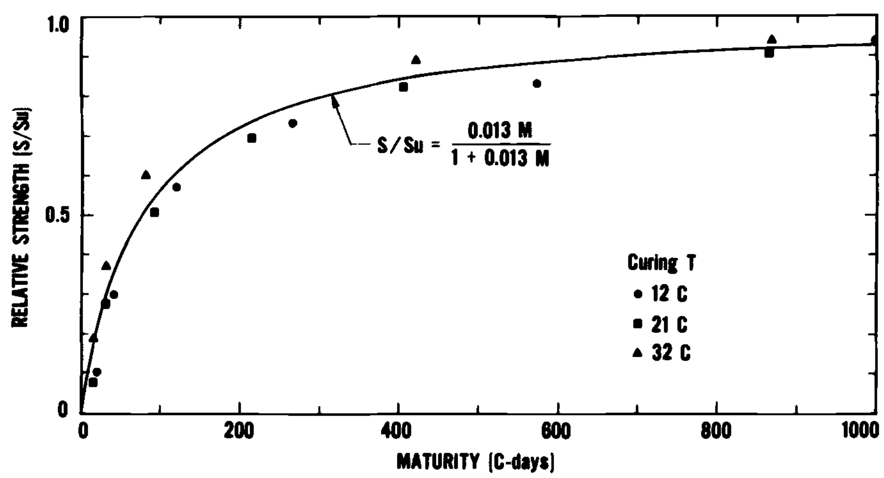

FIG. 9—*Relative strength versus maturity for isothermally cured concrete specimens using datum temperature of −10°C.*

APPENDIX

Suppose we desire to use the maturity method to determine when formwork can be removed safely or when cold weather temperature protection can be terminated. The first step would be to establish, by a testing program, the relative strength versus maturity relationship of the concrete to be used, that is, the values of A and M_o would be determined by using Eq 12

$$S/S_u = [A(M - M_o)]/[1 + A(M - M_o)]$$

To express the relative strength in terms of the 28-day standard cured strength S_{28}, we would calculate the maturity value for this curing condition and use Eq 12 to calculate S_{28}/S_u. If the value of this ratio is $1/\beta$, then it follows that

$$S/S_{28} = [\beta A(M - M_o)]/[1 + A(M - M_o)] \quad \text{(A1)}$$

The maturity value required to achieve any desired value of S/S_{28} can be calculated. By rearranging Eq A1, we obtain

$$M = M_o + [\alpha/A(\beta - \alpha)] \quad \text{(A2)}$$

where α is the desired value of S/S_{28}. As an example, suppose the following values have been determined for the concrete

$$A = 0.027\ (°\text{C-day})^{-1}$$

$$M_o = 2.2°\text{C-day}$$

$$T_o = 4°\text{C}$$

The maturity M_{28} for 28 days at 23°C would be

$$M_{28} = 28(23\text{-}4) = 532°\text{C-day}$$

By substituting this maturity value into Eq 12, we would find that $\beta = 1.07$. Suppose that an analysis of construction load effects indicates that formwork can be safely removed when the in-place concrete strength is 75% of the 28-day strength, that is, when $\alpha = 0.75$. Using Eq A2, the required maturity for form removal would be

$$M = 2.2 + [0.75/0.027\ (0.07\text{-}0.75)] \approx 85°\text{C-day}$$

The time t_{req} required to achieve this maturity value would depend on the cumulative average concrete temperature T_a

$$t_{req} = M/(T_a - T_o)$$

For example, for an average concrete temperature of 10, 20, or 30°C, the required times would be 14, 5.3, or 3.3 days, respectively. Conversely, we can determine the required cumulative average concrete temperature to permit form removal at a fixed schedule. As an example, for form removal at an age of four days, the average concrete temperature during those four days would have to be at least

$$T_a = M/t + T_o = (85/4) + 4 \approx 25°\text{C}$$

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