Cement and Concrete Research 40 (2010) 58–65

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Unified modeling of setting and strength development

R.C.A. Pinto [a,*], A.K. Schindler [b]

[a] Department of Civil Engineering, Federal University of Santa Catarina, Florianópolis, SC 88040-910, Brazil
[b] Department of Civil Engineering, Auburn University, Harbert Engineering Center, Auburn, AL 36849, USA

ARTICLE INFO

Article history:
Received 19 December 2008
Accepted 13 August 2009

Keywords:
Maturity method
Aging (C)
Compressive strength (C)
Temperature (A)

ABSTRACT

The effect of temperature on the development of concrete compressive strength can be modeled by the maturity approach once the temperature sensitivity of the mixture, quantified by the activation energy (E_a) of its chemical reactions, is known. It is common in maturity applications to use a unique value of E_a obtained for the hardening period, even though the effect of temperature is different on the rate of setting and hardening. E_a-values presented in the literature suggest that the temperature sensitivity is lower before hardening. This paper proposes a new approach to the traditional maturity method unifying the distinctly different temperature sensitivities before final setting and during hardening. Results of setting and compressive strength of mixtures with different cementitious materials were analyzed with activation energy values calculated for the periods before final setting and during hardening. For the investigated mixtures, the new approach led to improved strength predictions, suggesting that it is useful to take into account setting behavior in the development of the strength–maturity relationship.

1. Introduction

The maturity approach has been used to model temperature effects on the development of concrete compressive strength since around 1950 when steam curing treatments were initially applied to accelerate compressive strength gain [1]. Maturity accounts for the combined effects of temperature and time on the development of compressive strength (and other properties such as setting, degree of hydration, etc.), being evaluated from the temperature history of the concrete investigated.

In maturity applications, a strength–maturity relationship is established for a given mixture cured at known temperature conditions. Several mathematical relationships for the strength–maturity relationship have been proposed since Saul [2] defined the term maturity, in 1951. An appropriate strength–maturity relationship should take into account the dormant period of a concrete mixture, in which the material is still in a plastic state. This is essential, as strength development starts at final set, and inaccuracies in the estimated final set time may affect the early-age predicted strength. The extent of this period is related to the setting behavior of the concrete mixture which depends on the curing history of the concrete [3].

The precise definition of the time when setting starts and ends is somewhat subjective, since setting is caused by a gradual stiffening process. Nevertheless, this transition period starts when concrete loses its plasticity, and ends when measurable mechanical properties start to develop [4]. The hardening period follows in which concrete continuously gains strength with time.

The setting and hardening processes are physical consequences of the chemical activity in a mixture, and thus, are greatly affected by temperature. Arrhenius-based maturity functions have been proposed to the setting and to the hardening periods [3,5]. The temperature sensitivity of a given mixture can be quantified by the apparent activation energy (E_a) of its chemical reactions [6].

Traditionally, when the maturity approach is used to estimate strength, a single value of E_a is used [7] for the periods preceding final set and during hardening, even though the temperature sensitivity of the cement hydration reactions decreases as they turn from chemically controlled to diffusion controlled [8]. Researchers have attempted to include variable E_a-values during the hardening period [9,10]; however, it is common practice to use a single E_a-value to estimate setting and strength development. Some values of activation energy reported in the literature [11–21] for mixtures with Type I cement and replacements of various supplementary cementitious materials, obtained for the setting and hardening periods are summarized in Table 1. While there is a wide range of values due to the composition of the mixtures, the reported activation energies up to final set are generally less than those reported for the hardening period, suggesting that there may be differences in temperature sensitivity during the setting and hardening periods. Thus, the utilization of a fixed E_a-value obtained for the hardening period may lead to poor estimates of strengths at very early ages since the temperature sensitivity of the mixture up to final set has not properly been taken into account.

* Corresponding author. Tel.: +55 48 3721 7768; fax: +55 48 3721 5191.
E-mail address: rpinto@ecv.ufsc.br (R.C.A. Pinto).

0008-8846/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2009.08.010

Table 1
Some activation energy values reported in the literature (kJ/mol).

	Reference	Activation energy from setting experiments — E_s	Activation energy for hardening period — E_a
Type I cement mixtures	Lachemi et al. [11]	30.2[a]	
	Lei and Strubble [12]	22.0[a]	
	Turcry et al. [13]	29.0[a]	
	Pinto and Hover [14]	37.9[a]	
	Garcia et al. [15]	29.6[b]	
	Wade et al. [16]	27.1 to 33.4[b,c]	
	Barnett et al. [17]		32.9 to 35.1[c]
	Carino and Tank [18]		43.6 to 63.6[c]
	Schindler and Folliard [19]		46.0
	Voigt et al. [20]		38.0
	Wirkin et al. [21]		35.6
Mixtures with fly ash	Wade et al. [16]	23.3 to 25.7[c,d]	
		27.0 to 29.0[c,e]	
	Carino and Tank [18]		30.0 to 36.6[c]
	Schindler and Folliard [19]		30.1 to 40.7[c,d]
			37.5 to 43.1[c,e]
Mixtures with GGBF slag	Wade et al. [16]	26.7 to 35.2[c]	
	Barnett et al. [17]		35.2 to 62.1[c]
	Carino and Tank [18]		42.7 to 56.0[c]
	Schindler and Folliard [19]		51.5 to 55.2[c]

[a] Up to initial set.
[b] Up to final set.
[c] Various w/cm ratio.
[d] Class F fly ash.
[e] Class C fly ash.

This paper proposes a new approach to the traditional maturity method to unify the distinctly different temperature sensitivities before setting and during the hardening period to improve the overall strength prediction of concrete at all ages. The effect of using different activation energies on the development of a strength–maturity relationship is assessed. Setting and compressive strength results of mortar and concrete mixtures incorporating different cementitious materials under various curing temperatures were analyzed with an activation energy value calculated for the period up to final set and another for the hardening period. For the somewhat limited mixtures investigated here, the proposed new approach led to improved strength predictions than the traditional maturity method. This result suggests that that strength predictions could be improved when the setting behavior is taken into account in the development of the strength–maturity relationship.

2. Review of the maturity approach to estimate compressive strength

According to the maturity rule proposed by Saul [2], a concrete mixture at a certain level of maturity attains the same strength regardless of the combination of time and temperature history to arrive at such maturity. The equivalent age maturity approach modifies the time-axis of the strength–age relationship by calculating a maturity index according to Eq. (1).

$$M(T_c, t) = \int_0^t f(T_c)dt \tag{1}$$

where,

$M(T_c,t)$ = maturity index,
$f(T_c)$ = a function of temperature,
T_c = concrete temperature, and
t = concrete age.

However, for most concrete mixtures, the level of ultimate strength development is affected by the early concrete temperatures [1]. Lower early curing temperatures often lead to higher ultimate strength, and vice versa. This effect is called the crossover effect and has been reported by various investigators [9,22]. It should be noted that the crossover effect does not occur in all types of mixtures [23]. If a concrete mixture is subjected to the crossover effect, the maturity rule as stated above will not be able to correctly estimate later-age strength, as a unique strength–maturity relationship does not exist. On the other hand, it can be shown that for a particular concrete mixture, there is a unique relationship between degree of hydration and maturity [24]. Considering that the degree of hydration can be assessed by the degree of strength development, i.e., the ratio between the strength at any time and the long-term strength, also called ultimate strength (which produces a relative strength), the maturity rule could thus be modified, and a unique relative strength–maturity relationship established. Carino [1] showed that a unique relationship between the relative strength ratio and maturity exists, even for mixtures that exhibit the crossover effect.

In 1956, Benhardt [25] proposed that the rate of strength gain at any age should be a function of the current strength and the temperature, as mathematically expressed in Eq. (2). According to the data analyzed in his paper, Benhardt believed that the value of the constant m in Eq. (2) is likely to be 2.

$$\frac{dS}{dt} = S_u\left(1 - \frac{S}{S_u}\right)^m k(T_c) \tag{2}$$

where,

S_u = ultimate strength,
S = compressive strength at age t,
$k(T_c)$ = rate constant, which is temperature dependent, and
m = constant.

Integration of Eq. (2), with the constant m being 2, can be performed assuming as the boundary condition that concrete strength starts to develop as soon as concrete is produced, resulting in the following expression:

$$\frac{S}{S_u} = \frac{kt}{1 + kt} \tag{3}$$

where,

kt = the result of the internal $\int_0^t k(T_c)dt$ (unitless).

One can notice that this integral corresponds to the maturity index as presented in Eq. (1). However, the assumption of the lower boundary condition is not strictly correct, since up to final setting the concrete is still a plastic material, and it is thus not able to develop any mechanical properties. The utilization of an offset time (t_o) as a lower boundary condition is then more appropriate, and Eq. (3) can thus be modified to Eq. (4). This function is commonly referred to as the "hyperbolic function" and is the preferred strength–age function in North American practice [7].

$$\frac{S}{S_u} = \frac{k(t - t_o)}{1 + k(t - t_o)}. \tag{4}$$

Maturity is often expressed in terms of equivalent age (t_e), which represents the curing age at a fixed reference temperature necessary to achieve the same level of maturity when cured at a different temperature history [5]. In this case, the chronological curing age of a concrete cured at any temperature is converted to an equivalent