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Discussion

A discussion of the paper "Application of degree of hydration concept and maturity method for thermo-visco-elastic behaviour of early age concrete" by Geert De Schutter ☆

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The potential for using the maturity method to predict early-age properties of concrete is demonstrated in this paper. This discussion focuses on the correlation between maturity, degree of cement hydration, and concrete properties. Further clarification of the statement that "…both methods (degree of hydration and maturity method) principally yield the same results and conclusions (for dealing with properties of early age concrete)" is considered important because it is misleading to equate maturity to cement hydration in this context. Maturity is a mathematical construct used to describe the development of a property of interest. This is achieved by utilizing the time integral of a temperature function of that property. It is important to recognize that properties of one concrete with different temperature sensitivities require that their maturities be formulated differently.

The discussion illustrates that the mathematical definition of the maturity used in the paper leads to the 'equivalence' conclusion referred to above. A brief review of how the maturity concept was formulated is presented to demonstrate the validity of the correlation between maturity, the degree of cement hydration and concrete properties. It is indicated that a generalized maturity approach may not be valid.

1. Equivalence of Guo's maturity function and degree of cement hydration

The key component of the maturity function [3] used in the paper was the cement hydration rate, $k(\theta,t)$ (Eq. (13) in the paper). The following derivation demonstrates the direct proportionality of this maturity function and the degree of cement hydration $\alpha(t)$ based on the exothermic character of the hydration process

$$\sum_{0}^{t} k(\theta,t) \times \Delta t = \int_0^t \left[\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{Q(\theta,t)}{Q_{\max}}\right) \cdot C\right] \mathrm{d}t = \frac{Q(\theta,t)}{Q_{\max}} \cdot C = \alpha(t) \cdot C, \quad (1)$$

with the notation having the same meaning as described in the paper. Eq. (1) confirms that the definition of this maturity function implies an equivalence to the degree of cement hydration. Two ways to assess a correlation of Guo's maturity function to the strength development are possible:

1) Validation by experiment; this is the common practice and was utilized by [3]. However, general conclusions should be avoided without a knowledge of the fundamental mechanisms underlying behavior.
2) Use of the assumption that a "temperature independent and linear relation" exists between the compressive strength and degree of hydration (Eq. (7) in the paper). However, it would be required that both the assumption and application of this maturity function be generally valid.

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2. Correlation between maturity and concrete properties

Freiesleben-Hansen and Pederson [2] conceptually modeled the cement hydration rate utilizing a degree of hydration function, $g(\alpha)$, where α is the degree of hydration, and a temperature function, $f(T)$, as seen in Eq. (2). The time integral of the temperature function of this model can be then directly correlated to the degree of hydration, as shown in Eq. (3).

$$\left.\frac{\mathrm{d}\alpha}{\mathrm{d}t}\right|_T = g(\alpha) * f(T) \tag{2}$$

$$\int_o^\alpha \frac{\mathrm{d}\alpha}{g(\alpha)} = \int_0^t f(T(t))\,\mathrm{d}t \tag{3}$$

They further generalized the definition of maturity expressing it as the time integral of the ratio of a temperature function $f(T)$ and the value of that function at a reference temperature T_{ref}:

$$M(t) = \int_0^t \frac{f(T(t))}{f(T_{\mathrm{ref}})}\,\mathrm{d}t \tag{4}$$

From Eqs. (3) and (4), it is clear that the maturity would be equivalent to the degree of hydration because of the temperature function used. However, in application it should be noted that this maturity function has been implicitly assumed to be able to predict the strength of concrete. It is understood that it is not the degree of cement hydration but the microstructure of concrete that directly determines its properties like strength, e.g., the transition zone between the aggregate and cement hydrates is a strength-limiting phase [5]. This maturity function is then questionable for concrete strength prediction.

Carino [1] proposed an approach that avoided this assumption and its consequences, by deriving a temperature function directly from a hyperbolic compressive strength developmental model for the maturity function. Further derivations from his hyperbolic model are made in this discussion as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{S(t)}{S_u}\right] = K(T)\cdot\left(1-\frac{S(t)}{S_u}\right)^2, \quad \text{and} \tag{5}$$

$$\int_{t_0}^t K(T)\,\mathrm{d}t = \int_0^{S(t)/S_u} \frac{\mathrm{d}\xi}{(1-\xi)^2} = \frac{S(t)/S_u}{1-S(t)/S_u} \tag{6}$$

where $K(T)$ is the temperature function (or rate constant), $S(t)$ is the strength at time t, S_u is the limiting strength, and t_0 is the time at which the strength development begins. Eq. (6) demonstrates that this 'maturity' can be mathematically equivalent to the compressive strength but not necessarily equivalent to the degree of cement hydration.

For a general concrete property (P), the maturity definition in Eq. (4) can also be utilized, assuming that $f(T)$ is a temperature function of that property [4]

$$\left.\frac{\mathrm{d}P}{\mathrm{d}t}\right|_T = g(P) * f(T) \tag{7}$$

where $g(P)$ is a function of the property P. For the same mathematical argument, the maturity constructed from this temperature function can be equivalent to the property P.

It is clear that the compressive strength and other concrete properties are dependent on the cement hydration, however, their temperature functions are not necessarily the same. Given this fact, Eq. (7) implicitly indicates that a maturity function for each property should be formulated with its own temperature function. A single maturity function for all properties of one concrete mix may not exist. Correlation between maturity, degree of cement hydration, and concrete properties assuming a single maturity function for one concrete mix is likely to be inappropriate. Satisfactory relationships between hydration kinetics, microstructure, and property development have not yet been established to warrant this assumption.

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