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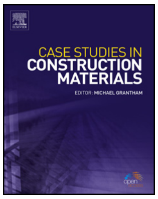

Critical analysis of strength estimates from maturity functions

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ABSTRACT

Strength estimates from the following maturity functions: Nurse-Saul, Rastrup, Weaver and Sadgrove, Freiesleben Hansen and Pedersen, and the Dutch Weighted Maturity have been compared with actual strengths of concretes cured with temperature histories of *in-situ* blocks, adiabatic and isothermal 50 °C curing. Three concrete mixes with a 28-day nominal cube compressive strength of 50 MPa have been investigated in this work. The first was a neat Portland cement mix whilst the other included partial cement replacement with fly ash (FA) and ground granulated blast furnace slag (GGBS) at 30 and 50% cement replacement levels respectively. High early age temperatures, such as those occurring in adiabatic or isothermal tests, appear to affect adversely the strength estimates and this is believed to be due to the detrimental effect of high curing temperatures on strength starting from a very early age. None of the maturity functions accounts for the detrimental effect of high curing temperatures on later age strength and thus all of them overestimate the later age strengths. It is believed that consideration of this detrimental effect in the maturity functions will improve the strength estimates for both early and later ages.

1. Introduction

The need for estimating the effects of steam treatments on strength development led, in around 1950, to the development of maturity methods which aimed at accounting for the combined effect of time and temperature on the strength development. An outgrowth of studies followed which dealt not only with accelerated curing but also with (a) estimation of in-place strength based on strength development data obtained under standard laboratory conditions [1–7] and (b) later age prediction based on early age strengths [8–10].

The interest in estimation of in-place strengths was the result of failures during construction blamed on premature removal of formwork. Two notable failures were: (a) the Skyline Plaza apartment building at Bailey's Crossroads in Fairfax Country, Virginia, which collapsed in March 1973 killing 14 workers and injuring 35 others [11], and (b) the Willow Island, West Virginia, cooling tower collapse in 1978 which killed fifty-six [12,13]. The benefits arising from accelerated construction schedules, e.g. faster formwork striking times resulting from real-time compressive strength monitoring, have led to the development and commercialisation of maturity meters [14–23]; from simple handheld ones to even wireless sensors transmitting information to smartphones.

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Numerous maturity functions [6,24–35] have been proposed and the ones that have gained popularity in the UK, USA and Netherlands [25,34,36–42] are briefly reviewed/described in the next section. Three concrete mixes with a 28-day nominal cube compressive strength of 50 MPa have been investigated in this work. The first was a neat Portland cement mix whilst the other included partial cement replacement with fly ash (FA) and ground granulated blast furnace slag (GGBS) at 30 and 50% cement replacement levels respectively. Strength estimates of these mixes cured under *in-situ*, adiabatic and isothermal (50 °C) conditions were determined and compared to actual values from cubes cured in the laboratory replicating these curing conditions. The accuracy of these estimates was the main focus of this work.

2. Maturity functions

The following maturity functions:

(a) Nurse-Saul [24,43],
(b) Rastrup [26],
(c) Weaver and Sadgrove [6]
(d) Freiesleben Hansen and Pedersen [35],
and,
(e) The Dutch Weighted Maturity [44–46],

are briefly reviewed/described below. Common to all of these is the need for a relationship between compressive strength and time/age or maturity index [25]. The Three Parameter Equation (TPE) has been suggested by Freiesleben Hansen and Pedersen (FHP) and is as follows [47]:

$$S = S_u e^{-\left(\frac{\tau}{t}\right)^{\alpha}} \tag{1}$$

where: S is compressive strength at age t (MPa),
S_u is the ultimate compressive strength (MPa),
τ is the characteristic time constant (days),
t is the test age (days),
α is a shape parameter.

2.1. The Nurse-Saul function

Saul [24] introduced the maturity concept/index, in 1951, which is a single factor, proposing that at the same maturity, for a given concrete mix, corresponds to the same strength regardless of the combination of temperature and time that make up that maturity:

$$M = \sum (T - T_0)\Delta t \tag{2}$$

where: M is the maturity (°C-days),
T is the average temperature (20 °C for standard curing) over the time interval Δt (°C),
T_0 is the datum temperature (°C),
Δt is the time interval (days).

The datum temperature corresponds to the temperature below which it is assumed that no strength gain occurs. In this work, the datum temperature was chosen to be equal to −11 °C, which is the average of what is recommended in the literature [34,48,49]. The above equation has become known as the Nurse-Saul function and assumes that the rate of strength development is a linear function of temperature. It can be used to convert a given temperature-time curing history to an equivalent age of curing at a reference temperature as follows:

$$t_e = \frac{\sum (T - T_0)}{(T_r - T_0)} \times \Delta t \tag{3}$$

where: t_e is the equivalent age at the reference temperature (days),
T_r is the reference temperature (°C).

Equivalent age represents the duration of the curing period at the reference temperature that would result in the same maturity as the curing period at other temperatures. Eq. (3) can be written as follows [25]:

$$t_e = \sum \beta \times \Delta t \tag{4}$$

and the age conversion factor, β, is:

$$\beta = \frac{(T - T_0)}{(T_r - T_0)} \times \Delta t \tag{5}$$