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A discussion of the paper "The maturity method: Modifications to improve estimation of concrete strength at later age" by Yahia A. Abdel-Jawad

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Abstract

Two modifications have been proposed for the Nurse-Saul maturity function to get better estimates of compressive strength of concrete cured at different temperatures in this paper. The modifications account for the effect of *w*/*c* ratio on the temperature dependence of strength development and the effect of curing temperature on the long-term strength. This discussion focuses on strength development behaviour of concretes cured at different temperatures. Aiming to understand the strength development of cement based materials relevant experimental studies on mortar and concrete specimens in the literature are evaluated.
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Keywords: Concrete; Maturity; Later age strength; Modification; Estimation

0. Introduction

To determine the development of strength of concrete with maturity, maturity-strength relationships were examined for concrete specimens produced with CEM II/B-M and CEM I 42.5 R at curing temperatures of 0, 23, 40 °C and testing age of 1, 3, 7, 14 and 28 days by Topçu and Karakurt [1]. The effect of curing temperature on strength development decreases with increasing age as slopes of the curves decreases for 1, 3, 7, 14 and 28 days in Fig. 1 below. Although a higher temperature at 1 and 3 days increases the strength, adversely the strength from about 7 days onwards decreased with the increasing temperature in concretes produced with CEM I 42.5 R. And a similar effect with a delay period observed in CEM II/B-M concretes.

Topçu and Toprak [2] investigated for the effect of early age curing time and temperature on later age strength. The cube concrete specimens produced with two different types of fine aggregate (RS, CS) gained early strength by application of two different cure cycles, 1-h preheating cure process, 6-h or 18-h cure process at 20, 40, and 60 °C at moisture over 50%. After the accelerated cure applications, 28-day specimens were kept in a curing tank at 20 °C until the time of the experiment. The cube compressive strength was obtained at the end of the cure applications and on the 28th day. The results are given in Fig. 2. It shows that the increase in curing temperature and time accelerates the early-strength gain of the concrete but affects the 28-day concrete strengths negatively.

Concrete specimens produced from the same mixture were kept at 1, 21, and 43 °C. Some of the specimens were kept in temperatures as above, and the others were kept at 21 °C after 6, 18, 30, and 48 h, respectively, and were tested in compression on the 1st, 3rd, 5th, 7th, and 28th days by Volz et al. [3]. From the results obtained, it was observed that the maturity-strength relationship, which was acquired after keeping the specimens at a normal temperature after

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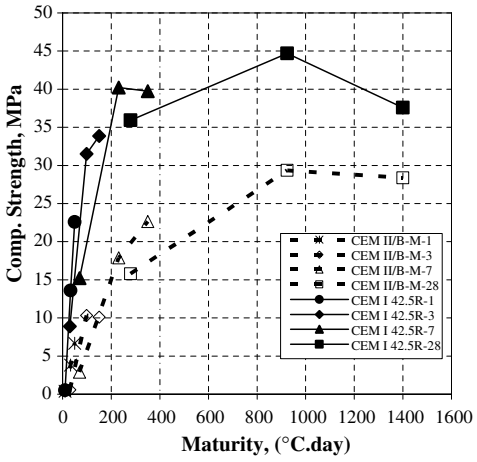


Fig. 1. Compressive strength–material relationship.

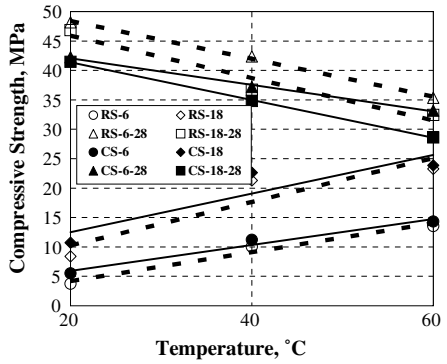


Fig. 2. Compressive strength–curing temperature relationship.

6, 18, 30, and 48 h, or at the first temperature, did not change permanently. Volz et al. explain that the curves form unity in themselves depending on the initial temperature, and that the initial curing temperature that lasts 6 h can affect the movement of the maturity-strength curve, and finally that late temperature variations do not change the curve.

The compressive results obtained for 24 h initial curing temperature and than standard moist curing at, 18 °C by Alou and Delisle [4] are given in Table 1 below. When the table evaluated negative effects of high temperature curing on compressive strength observed above 7 days and the decrease of strength ratio reaches considerable values for high temperatures. But in low temperatures except a delay of strength development up to 7 days, no significant effects on strength observed.

Table 1
Compressive strength-age results due to initial curing temperature

Time (day)	Cube compressive strength (MPa)							
	4 °C		18 °C		31 °C		55 °C	
	f_c	%	f_c	%	f_c	%	f_c	%
1	–	0	7.1	100	10.2	144	15.5	218
2	9.1	70	13.0	100	14.7	113	15.5	119
7	26.9	103	26.1	100	26.0	100	18.3	70
28	36.2	105	34.4	100	32.6	95	23.1	67
90	45.0	103	43.9	100	41.7	95	32.2	73
232	50.3	101	49.8	100	46.2	95	40.3	82

Although a higher temperature during placing and setting increases strength in the very early stages, it may adversely affect the strength from about 7 days onwards. When the table evaluated the dominant effect on later age strength have to be considered as early age (24 h) concrete temperatures and mixture hour.

According to the maturity concept, the concrete will have the same strength when it has achieved the same maturity index, regardless of the combination of time and temperature used to calculate the maturity index. Therefore, the concrete will reach the same strength at two temperatures, T_a and T_s, when

$$(T_a - T_0) \cdot t_1 = (T_s - T_0) \cdot t_e \quad (1)$$

In other words, the curing time needed at the specified temperature, T_s, to produce the same strength obtained at the curing temperature, T_a, will be equal to

$$t_e = (T_a - T_0) \cdot t_1 / (T_s - T_0) \quad (2)$$

This curing time is known as the equivalent age (t_e) at specified (or reference) temperature (T_s) to produce the same strength of a concrete cured at another temperature (T_a) for a certain time (t_1).

1. Modification account for the effect of *w/c* ratio on the temperature dependence of strength development

Modification to account better for the strength development of concrete at different curing temperatures to the equivalent age, the role of the concrete w/c ratio involved in Eq. (7) in the paper is as follows:

$$t_e = [(T_a - T_0)/(T_s - T_0)]^n \cdot \Delta t \quad T_0 = -10\,^\circ\mathrm{C} \quad (3)$$

where n will account for the role of w/c ratio and is given by the following equation:

$$n = 1/[1 - (w/c)^2] \quad (4)$$

Abdel-Jawad evaluated the maturity and compressive strength results of Carino and Detwiler. According to the Eq. (4) n is calculated as 1.23 and 1.46 for 0.43 and 0.56 w/c ratios of same mixture mortars by Carino [6], which were used by Abdel-Jawad in the paper too. For the curing temperatures higher than reference temperature Eq. (3) will account bigger equivalent age values as the w/c ratio increases. Thus the estimated compressive strength values calculated according to equivalent age will increase as the w/c ratio increases. This is contrary to fundamental mechanism of strength development neither at early nor at later ages. This can be seen obviously by the experimental results in the literature by Carino [6], Kim and Moon [7], Oluokun et al. [8]. Experimental results of Kim [9] is given in Table 3 below as an example. As illustrated in the table in all curing temperatures and at all ages, compressive strength results are bigger for the smaller w/c ratio.

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In an other point of view if we consider t_0: (age when strength development is assumed to begin (day)), k_t, k_r (value of rate constant at a standard temperature (day^{-1})and value of rate constant during a time interval (day^{-1}), respectively); we see that t_0 decreases with the increasing w/c ratio, k_t and k_r decreases with the increase in w/c ratio for all curing temperatures as illustrated in the literature [6,10]. Thus the compressive strength development rate decreases when w/c increases. Thus the modification by Abdel-Jawad is invalid. The w/c ratio can be used to modify limiting strength or rate constants. A modification in this format may be valuable on non isothermal curing conditions according to the moisture loss in high temperatures.

2. Modification account the effect of curing temperature on the long-term strength

The higher the initial curing temperature, the higher the early-age strength, but the lower the later-age strength as illustrated in the literature. Therefore, to quantitate this effect and to account for it when estimating compressive strength using the strength development at a reference temperature the ratio between the actual strength obtained for concrete at a given age (t) at certain curing temperature (T_a) to that estimated using the maturity equation (Eq. (3)) in our notation for a reference temperature (T_s) is plotted against the temperature ratio, $(T_a - T_s)/T_s$ by Abdel-Jawad. The reference temperature (T_s) used in was 20 °C. To account effect of curing temperature on the long-term strength the equation below is given.

$$f_c(t, T_a)/f_c(t_e, T_s) = 1 - k \cdot (T_a - T_s)/T_s \quad (5)$$

The relationship between k and the equivalent age was described in the paper by Eq. (6)

$$k = 0.14(1 - e^{-0.1t_e}) \quad (6)$$

Therefore combining Eqs. (5) and (6) the following equation is obtained:

$$f_c(t, T_a) = f_c(t_e, T_s)[1 - 0.14((T_a - T_s)/T_s)(1 - e^{-0.1te})] \quad (7)$$

When we evaluate the Eq. (7) for experimental results by Kim and Moon [7] Table 4 for 5 °C and 28 day according to equivalent age Eq. (2); the compressive strength will be equal to (1.08) × 14 day strength at 20 °C (reference temperature) for isothermal curing process. According to experimental results 28 day strength at 5 °C = 29.9 MPa, 14 day strength at 20 °C = 31.7 MPa Thus there is no need to increase the strength by a modification as given at Eq. (7). Considering Table 1 in the paper, compressive strength results by Kjelsen and Detwiler [11] are approximately equal at 5 °C and 20 °C temperatures after 28 day. Therefore we do not have to use equivalent age.

The changing of the compressive strength of ordinary and high performance concrete after having cured at low

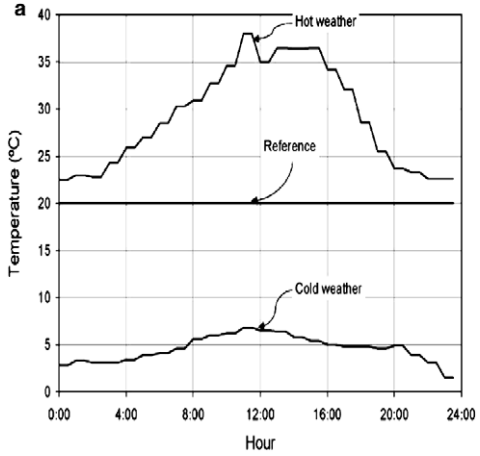


Fig. 3. Climatic chamber.

Table 2
Slump and compressive strength values for 7 and 28 days

Mixing hour	Slump (cm)	Compressive strength (MPa) (Coefficients of variation (%))	
		7 days	28 days
Hot weather conditions			
Reference	9.0	37.9 (0.2)	43.3 (4.6)
10.00	4.5	34.3 (2.5)	40.9 (5.2)
11:30	3.5	34.4 (3.2)	41.1 (2.9)
13:00	3.5	35.2 (4.6)	41.9 (2.8)
14:30	4.0	36.8 (3.6)	41.5 (3.5)
17:30	3.2	37.3 (3.2)	42.5 (6.6)
Cold weather conditions			
Reference	9.0	37.9 (0.2)	43.3 (4.6)
8:15	7.0	41.7 (2.2)	45.8 (2.8)
10.00	7.5	41.7 (4.4)	45.7 (1.5)

Table 3
Compressive strength (MPa) of type I cement concrete for different w/c ratios

Cure temperature (°C)	$w/c = 0.40$				$w/c = 0.50$			
Cure time (day)	1	3	7	28	1	3	7	28
10	5.4	22.1	36	51.3	3.5	14.3	24.7	36.9
23	20.9	31.6	41.5	50.8	9.4	23.4	31.5	42.4
35	22.8	34.6	39.2	49.4	17.1	24.2	33.1	41.3
50	31.7	35.8	43.6	48.7	19.8	28.1	34.6	39.3

Table 4
Compressive strength results at three different isothermal curing temperatures

Cure temperature (°C)	1 day	2 day	3 day	7 day	14 day	28 day
20	6.96	12.1	16.4	25.1	31.7	35.9
40	15.4	20.1	21.3	24.7	28.5	32.5
5	0.98	3.14	5.69	12.9	18.7	29.9

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Table 5
The average compressive strength of concrete and decrease of strength ratio

Production	Curing time and conditions	Age (days)	Ordinary concrete		High performance concrete	
			Average compressive strength (MPa)	Decrease of strength ratio (%)	Average compressive strength (MPa)	Decrease of strength ratio (%)
1st	−5 °C, 7-day	7	2.7	79	16.3	63
	Standard cure, 7-day	7	13.1		44.1	
	−5 °C, 7-day and standard cure, 21-day	28	4.8	79	30.6	41
	Standard cure, 28-day	28	22.4		51.8	
2nd	0 °C, 7-day	7	5.3	62	30.1	33
	Standard cure, 7-day	7	14.0		45.2	
	0 °C, 7-day and standard cure, 21-day	28	11.5	50	37.0	32
	Standard cure, 28-day	28	23.0		54.1	
3rd	+5 °C, 7-day	7	20.5	44	33.8	26
	Standard cure, 7-day	7	13.5		45.5	
	5 °C, 7-day and standard cure, 21-day	28	13.8	38	41.5	24
	Standard cure, 28-day	28	22.4		54.8	
4th	10 °C, 7-day	7	8.9	30	36.0	20
	Standard cure, 7-day	7	12.7		45.0	
	10 °C, 7-day and standard cure, 21-day	28	14.9	30	43.5	19
	Standard cure, 28-day	28	21.4		54.0	

temperature was investigated experimentally by Husem and Gözütok [12]. To accomplish this purpose, concrete specimens of 150 mm diameter and 300 mm high were prepared. After their production the specimens were cured at different conditions for 7 days. Some of them were at 23.2 °C (standard curing); the others were at 10, 5, 0 and −5 °C, respectively. In the 7th day, some of the specimens cured at different temperature (10, 5, 0 and −5 °C) were broken under uniaxial compression. On the other hand, some of the specimens were applied to standard curing during 28 days. In the end of 28 days, compressive strength of all specimens was obtained. According to the results, compressive strength of the specimens at 10 °C and less than 10 °C during 7 days were lower than that of the specimens at standard curing. According to Table 5 concrete at low temperatures have smaller values of strength both at 7 and 28 days adversely to the modification given by Abdel-Jawad.

Modification given by the author modificates practically estimates in high temperatures by decreasing the later age strength, depending on difference to reference temperature and the factor k given in Fig. 3. This modification increases the estimates in cold temperatures at the same rate considering only the difference to reference concrete temperature.

But the behaviour of concrete in cold and hot weathers are significantly different. When Tables 1–4 evaluated for low temperatures; it is concluded that curing time in low temperature has the dominant effect on later age strength and the time the concrete strength cured in low temperature to reach to strength of standard cured concretes differs according to this phenomenon. As a conclusion correlation with equivalent age is misleading.

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