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A humidity-adjusted maturity function for the early age strength prediction of concrete

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ABSTRACT

The early age strength development of concrete is determined by a proposed maturity method, which considers not only the curing temperature history at the core of the concrete specimens, but also the relative humidity of the environment. The humidity factor is incorporated with the original rate constant model to form a new maturity function for the prediction of concrete strength development. In order to calibrate this humidity-adjusted rate constant, compression tests were conducted on concrete cylinders cured at different conditions of temperature and humidity. By comparing the ratio of rate constants of concrete cylinders cured at the same temperature but different humidities, the humidity factor could be quantified. Verification programs (including concrete cylinders cured at the programmed temperature and relative humidity, submerged in water baths and cured outdoors, and air-dried outdoors) were used to determine the applicability of the prediction model. Experimental results show that this new maturity function is able to predict the in-place strength development of ordinary concrete cylinders at early age with a maximum difference of 10%.

1. Introduction

The strength development of concrete is a function of curing temperature and age, described by the so-called maturity function [1,2]. Saul proposed a summation of temperature over the curing period as the maturity function, in which the datum temperature of −10.5 °C was recommended [3]. Saul also presented the maturity concept as: concrete of the same mix at the same maturity has approximately the same strength whatever combination of temperature and time make up the maturity. However, several researchers [4,5] found that this temperature–time factor (or Nurse–Saul function) underestimated the influence of temperature on the strength development of concrete at early age and overestimated it at later maturity. This drawback comes from the assumption that temperature has a linear effect on the strength development [6]. Based upon the Arrhenius equation, Hansen and Pedersen [7] proposed an equivalent age to convert the age of concrete cured at different temperature to an age at a reference temperature. This equivalent age was related to the activation energy of the concrete mix. The apparent activation energy is not a constant for a curing temperature below 20 °C [7]. Recent study shows that the apparent activation energy depends on temperature as well as curing age [8].

The main purpose of the maturity method is to predict the strength gain of a concrete structure after a certain curing period, so that the construction schedules could be accelerated and catastrophic failure during formwork removal could be avoided. Usually, the strength gains of concrete and mortar specimens as a function of maturity index should be established first [9–11]. The measured temperature history of the concrete specimens in the field can be transformed into a maturity index (e.g., rate constant or equivalent age), and the in-place strength can be estimated. Several laboratory and field tests have been performed to verify the applicability of various maturity functions [11–13]. For example, Lachemi et al. have successfully applied the maturity method to predict the setting time in slipforming operations [14]. Detailed review of procedures to calibrate the maturity index of a given concrete mix and methods to estimate the in-place strength of concrete using the laboratory built strength–maturity relation can be found in Malhotra and Carino [6].

To date, most of the maturity models are based upon mortar cubes or concrete cylinders cured at 100% relative humidity (100% RH). However, insufficient water or moisture supply often occurs during the curing period of the site-cast concrete. These existing maturity models usually overestimate the strength gain of the concrete cured outdoors. Since the relative humidity of the in-place concrete structure is not always 100% RH, it is necessary to consider the influence of the relative humidity on the strength development of the concrete. Although the internal moisture state and surface to volume ratio will affect the hydration rate of a

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concrete structure, this paper only considers the relative humidity of the environment and the temperature at the concrete core as the dominant factors for the strength development of concrete, since both quantities are feasible to measure during the curing period of the site-cast concrete. Moreover, humidity of the environment can be obtained from the local weather record. This study proposes a humidity-adjusted equivalent age of concrete and a procedure to calibrate the rate constant as a function of the curing temperature and the environmental relative humidity. This humidity-adjusted rate constant model reduces to a conventional rate constant model under 100% RH. Some verification programs are performed to estimate the strength gain of concrete cured under variable temperature and relative humidity.

2. Humidity-adjusted rate constant model (HARCM)

Based upon previous arguments, a proper maturity function should consider the influence of the relative humidity on the strength development of the concrete. Therefore a humidity-adjusted rate constant $R_{T,h}$ is proposed as

$$R_{T,h} = A(T,h)\cdot e^{(B\cdot T)} \tag{1}$$

where A is a regression constant obtained from the compression data of concrete cylinders or mortar cubes cured at different humidities h and curing temperature T, and B is a temperature sensitivity factor. It is noted that A depends on both humidity and temperature, which is different from the form used by Tank and Carino [11]. When h is 100% RH, A will reduce to the form as in [11]. For simplicity, the maturity function proposed by Tank and Carino [11] will hereafter be denoted as the TC method.

In this study, the humidity factor J_h is defined as

$$J_h = \frac{R_{T_c,h}}{R_{T_c,h_r}} \tag{2}$$

where $R_{T_c,h}$ is the rate constant for concrete cured at a fixed temperature T_c, with relative humidity h%, and R_{T_c,h_r} is the rate constant for concrete cured at the same temperature T_c, with reference curing relative humidity h_r. A calibration test to obtain the value of J_h is necessary. In order to calibrate the humidity factor, it is suggested that concrete cubes or cylinders be cured at three different temperatures and four relative humidities for each temperature condition. Concrete specimens cured in water baths are considered as the 100% RH curing condition, which is the same as the conventional maturity method. The rate constant $R_{T,h}$ is obtained from the regression data of the concrete compressive strengths at different ages, and the humidity factor J_h as defined by Eq. (2) can be obtained. Experimental data reveal that the relation between the humidity factor J_h and relative humidity h can be accurately fitted by a reverse hyperbolic curve as

$$J_h = \frac{J_u k_h (h^* - h_0)}{1 + k_h (h^* - h_0)} \tag{3}$$

where $h^* = 100 - h$, J_u is the nondimensional regression limiting humidity factor, k_h is the humidity rate constant from the data regression with dimension $(\%\,\mathrm{RH})^{-1}$, and h_0 is the regression initial humidity constant (% RH). Experimental data (which will be demonstrated later) show that h_0 is almost constant irrespective of the curing temperature. By imposing that J_h equals one when h equals h_r(=100), we have

$$k_h = \frac{1}{h_0(1 - J_u)} \tag{4}$$

The constant J_u varies linearly with the curing temperature. It is interesting that Eq. (3) has the same reverse hyperbolic form as the strength gain versus maturity relation proposed by other authors [11,13]. From Eqs. (1)–(3), the humidity-adjusted rate constant (or modified rate constant) can be expressed as

$$R_{T_c,h} = R_{T_c,100}\cdot\frac{J_u k_h (h^* - h_0)}{1 + k_h (h^* - h_0)} = A_{100} e^{B\cdot T_c}\cdot\frac{J_u k_h (h^* - h_0)}{1 + k_h (h^* - h_0)} \tag{5}$$

where A_{100} is the same A as shown in [11], which is the regression constant obtained from concrete specimens cured at 100% RH.

The humidity-adjusted affinity ratio γ', which is the ratio of the rate constant of concrete cured at arbitrary temperature and relative humidity during time interval Δt to the rate constant for curing at the reference temperature and reference relative humidity, can be defined as

$$\gamma' = \frac{R_{T,h}}{R_{T_r,h_r}} = e^{B(T-T_r)}\cdot\frac{J_u}{J_{ur}}\,\frac{k_h(h^* - h_0)}{1 + k_h(h^* - h_0)}\cdot\frac{1 + k_{h_r}(h_r^* - h_0)}{k_{h_r}(h_r^* - h_0)} = e^{B(T-T_r)}\cdot\frac{h_0 - h^*}{h_0 - h^*/J_u} \tag{6}$$

where h_r denotes the reference relative humidity, which is 100% RH in this study, k_{h_r} represents the humidity rate constant at reference temperature T_r, h^* is $100 - h$, while $h_r^* = 100 - h_r = 0$, and J_{ur} is the regression humidity constant at T_r. In the derivation of Eq. (6), the relation in Eq. (4) is applied for simplification. It is evident that when h equals h_r, γ' will reduce to the affinity ratio as that defined by TC method [11]. The humidity-adjusted equivalent age t_e' can be obtained as

$$t_e' = \sum \gamma' \Delta t \tag{7}$$

The strength gain for concrete cylinders cured at arbitrary temperature and humidity history can be calculated from the humidity-adjusted rate constant model (HARCM) as

$$S = S_u\cdot\frac{R_{T_r,h_r}(t_e' - t_{0r}')}{1 + R_{T_r,h_r}(t_e' - t_{0r}')} \tag{8}$$

$$R_{T_r,h_r} = A_{100}\cdot e^{(B\cdot T_r)}\cdot\frac{J_{ur}k_{h_r}(h_r^* - h_0)}{1 + k_{h_r}(h_r^* - h_0)} = A_{100}\cdot e^{(B\cdot T_r)} = k_r \tag{9}$$

where S_u is the regression limiting strength of concrete of the same mix, t_e' is the humidity-adjusted equivalent age following the transformation law given by Eqs. (6) and (7), t_{0r}' is the initial strength development age (days) at the reference temperature T_r and reference humidity h_r. From Eq. (9), R_{T_r,h_r} will equal to k_r, and t_{0r}' equal to t_{0r} as those defined by TC method [11]. However, the humidity-adjusted equivalent age t_e' considers the humidity effect on the strength development of concrete. The importance of this humidity factor on the strength gain of concrete cylinders will be demonstrated in the experimental part of this study. It is noted that S_u is a function of curing temperature and relative humidity. Curve fitting to obtain $S_u(T,h)$ is necessary. By taking the strength difference between two consecutive time steps using Eq. (8), the strength gain of a concrete specimen can be evaluated from the following incremental equation

$$S = \sum \mathrm{d}S = \sum \frac{S_u R_{T_r,h_r}\Delta t_e'}{[1 + R_{T_r,h_r}(t_e' + \Delta t_e' - t_{0r}')][1 + R_{T_r,h_r}(t_e' - t_{0r}')]} \tag{10}$$

where $\Delta t_e'$ is the humidity-adjusted equivalent age increment, which is the age difference between two consecutive humidity-adjusted equivalent ages calculated from Eqs. (6) and (7).

3. Experimental procedures

3.1. Calibration test

In order to apply the humidity-adjusted rate constant model to estimate the strength gain of concrete cylinders, the constants A_{100}, B, J_u, k_{h_r}, h_0, t_{0r}' and $S_u(T,h)$ in Eqs. (8) and (9) have to be determined from a standard calibration test. For a specified concrete mix, three constant curing temperatures of 12 °C, 27 °C and 40 °C, were adopted in this study. The relative humidities were set at 100% RH (cured in water baths), 90% RH, 80% RH and 70% RH for each temperature, respectively. A thermocouple was inserted into the core of the concrete cylinder during the casting of the concrete specimen. This thermocouple was connected to the data acquisition system to record the temperature of the concrete cylinder every 5 min. By measuring the penetration resistance on mortar sieved from the fresh concrete as specified by ASTM C403/C403M, the setting time of concrete could be determined. The 1×, 2×, 4×, 8×, 16× and 32× final set time were scheduled as the compression test dates for the concrete cylinders as shown in Table 1.

Three concrete mixtures were used in the experimental program. Type I OPC, river sand, and gravel were used as the basic materials. The gravel has a SSD relative density of 2.60, with water absorption of 1.68%, and moisture content of −1.24%. The maximum diameter of the gravel is 12.7 mm.The river sand has a SSD relative density of 2.50, with absorption of 2.04%, and a moisture content of −1.79%. The fineness modulus of the fine aggregate was 2.46. The cement has a relative density of 3.15. There was no admixture used in this study. Concrete cylinders were cured according to the ASTM standard C31-83. Table 2 shows the mix proportioning of the three mixes. The f_c' represents the 28 day design strength. The slumps of the 21 MPa and 35 MPa concrete batches were 20.5 cm and 16 cm, respectively. The dimensions of the concrete cylinders used in this study were ϕ7.5 cm × 15 cm. After casting the hardened concrete specimens were kept inside a temperature and humidity controlled cabinet or water baths according to the designed curing conditions. Before the final set time, the concrete specimens were kept within the steel mould and inside the temperature/humidity controlled cabinet. Care was taken for the low temperature and low humidity specimens. Each set of concrete compression data represents three cylinders. Since there are 12 kinds of temperature and humidity variations with six scheduled testing dates and three specimens as a test set, and two additional specimens needed to record the curing temperature of each curing condition, the total amount of concrete cylinders used in the calibration test for a specified mixture was 240. If the degree of hydration of a concrete specimen as a function of environmental curing humidity/temperature can be derived from some theoretical approach, then the amount of concrete cylinders needed in the calibration test could be reduced. Fig. 1 shows the procedure of the calibration test.

3.2. Verification program

Three kinds of verification programs were performed to examine the applicability of the proposed humidity-adjusted rate constant model. In the first program, concrete cylinders of the same mixture were cured within a chamber according to the pre-programmed temperature and humidity variations. The humidity varied between 75% and 85% RH, and the curing temperature varied from 27 °C to 36 °C. Compressive strengths of the concrete specimens were measured at designated ages of 1, 2, 3, 5, 7 and 14 days, respectively. Pico RH02 temperature/humidity transmitters were used to record the humidity histories of the curing cabinet and concrete specimens.

Concrete cylinders submerged in an outdoor water bath were the second program to simulate the ideal in-field curing condition. The relative humidity was 100% in this case. Only the temperature histories of the concrete cores were recorded through the thermocouples. In the last program, concrete specimens were air-dried outdoors to simulate the real field curing condition. Both temperature history at the concrete core and the environmental humidity were recorded through an AD/DA card. Specimens were removed on the same scheduled dates as the first program to measure their strengths. All the compressive strength data were compared with the strength gains predicted from the humidity-adjusted rate constant model. Since the concrete mixture used in the verification programs should be the same as the calibration test, only the different curing conditions for the verification programs are demonstrated in Fig. 1.

Table 1
Scheduled dates for compression test (1× = setting time at 100% RH)

Temperature (°C)	1× (h)	2× (h)	4× (h)	8× (h)	16× (h)	32× (h)
12.0	13	26	52	104	208	416 (17.33 days)
27.0	7.25	14.5	29	58	116	232 (9.67 days)
40.0	5	10	20	40	80	160 (6.67 days)

Table 2
Mix proportions of concrete

Specimen		Unit weight (kg/m^3)				Air content (%)
f_c' (MPa)	w/c (%)	Water	Cement	Sand	Gravel	
21	0.81	240	289	924	734	2
35	0.63	240	375	853	734	2
56	0.44	240	539	718	734	2

4. Results and discussion

4.1. Humidity and temperature dependence of the rate constant

For simplicity, only the results of the 21 MPa concrete cylinders are reported here. The strength–age data for concrete cured at different temperatures and humidities are given in Table 3. These data were used to calculate the constants $R_{T,h}$ in Eq. (1) and t_0 and S_u defined by other authors [11,13] (see Table 4). It is noted that $R_{T,h}$ is similar to k_T as defined in TC method, therefore a least square regression analysis can be used to obtain these three constants. In this paper, $R_{T,h}$ is adopted as the rate constant instead of k_T, since $R_{T,h}$ is both temperature and humidity dependent. Figs. 2–4 show the strength–age data for the 21 MPa concrete cylinders cured at 40 °C, 27 °C and 12 °C with different humidities, respectively. Each strength data represents an average from three concrete cylinders with a standard deviation of less than 6% in most cases. Fig. 5 summarizes the humidity-adjusted rate constant $R_{T,h}$ as a function of curing temperature using Eq. (1). It is seen that the humidity-adjusted rate constants vary exponentially with the temperature (Fig. 5). As expected, the limiting S_u decreased with increasing temperature (see Table 4), which exhibits the same trend as that reported by other researchers [11,13]. Furthermore, for the same curing temperature the limiting S_u increased with increasing relative humidity. However, for the same curing temperature, the humidity-adjusted rate constant $R_{T,h}$ decreased with increasing humidity (see Fig. 5). The larger difference of the humidity between the concrete core and the outer environment might accelerate the water migration and mass transport phenomenon inside the concrete cylinder, which will experience a higher $R_{T,h}$ at a lower humidity at early ages.

The values of A and B at different humidities are listed in Table 5. It is interesting that the constant B is almost invariant with the relative humidity. An average value of B = 0.05511 (1/°C) is adopted as the temperature sensitivity factor in this study. Table 5 reveals that the coefficient A in $R_{T,h}$ decreases with curing humidity; therefore it is necessary to quantify the influence of the humidity on the magnitude of $R_{T,h}$.

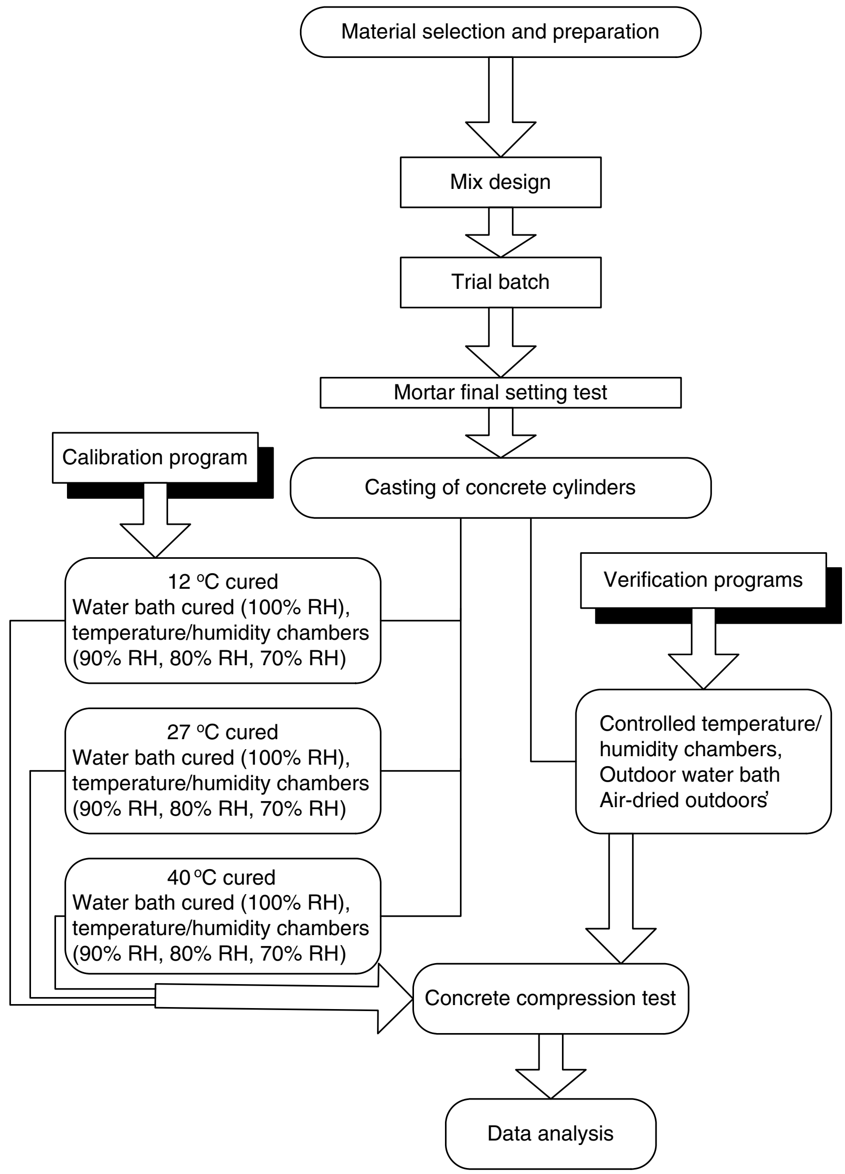

Fig. 1. Experimental procedures for calibration test of the humidity factor and maturity verification program.

Table 3
Compressive strengths for 21 MPa concrete cured at different temperature and relative humidity (Specimen: $\phi75 \times 150$ mm)

Curing temperature T_c (°C)	Age (days)	Strengths (MPa) at different humidities			
		70% RH	80% RH	90% RH	100% RH
12	0.54	0.41	0.48	0.70	0.76
	1.08	1.64	1.74	2.08	2.36
	2.17	3.82	4.51	4.77	4.96
	4.33	7.32	7.73	8.44	9.36
	8.67	9.46	10.80	12.47	14.38
	17.33	12.19	13.28	14.97	18.47
27	0.30	0.50	0.64	0.73	0.63
	0.60	2.14	2.44	3.05	2.76
	1.24	4.64	4.74	4.99	5.36
	2.42	7.46	7.87	8.49	9.66
	4.83	11.41	11.90	12.40	15.31
	9.67	12.86	14.11	14.98	19.58
40	0.21	0.64	0.68	0.76	0.80
	0.42	2.23	2.58	2.65	2.85
	0.83	5.13	5.46	6.00	6.55
	1.75	7.94	9.05	10.05	10.88
	3.33	10.45	11.68	12.64	15.27
	6.67	10.99	12.84	13.91	17.41

Table 4
The rate constants $R_{T,h}$ for 21 MPa (3000 psi) concrete cylinders cured at different temperature and relative humidity

Humidity	T_c (°C)	S_u (MPa)	$R_{T,h}$ (days^{-1})	t_0 (days)
100% RH	40	22.97	0.5435	0.1421
	27	27.34	0.2697	0.2150
	12	27.83	0.1199	0.3075
90% RH	40	17.55	0.7156	0.1446
	27	19.82	0.3450	0.2025
	12	21.20	0.1497	0.3163
80% RH	40	15.86	0.7420	0.1483
	27	18.44	0.3646	0.2033
	12	18.50	0.1590	0.3729
70% RH	40	13.71	0.7753	0.1454
	27	16.96	0.3753	0.2217
	12	16.65	0.1636	0.3858

4.2. Calibration of humidity factor J_h

In order to calibrate the humidity factor J_h in Eq. (2), the ratios of $R_{T_c,h}$ to $R_{T_c,100}$ are evaluated and listed in Table 6. The distribution

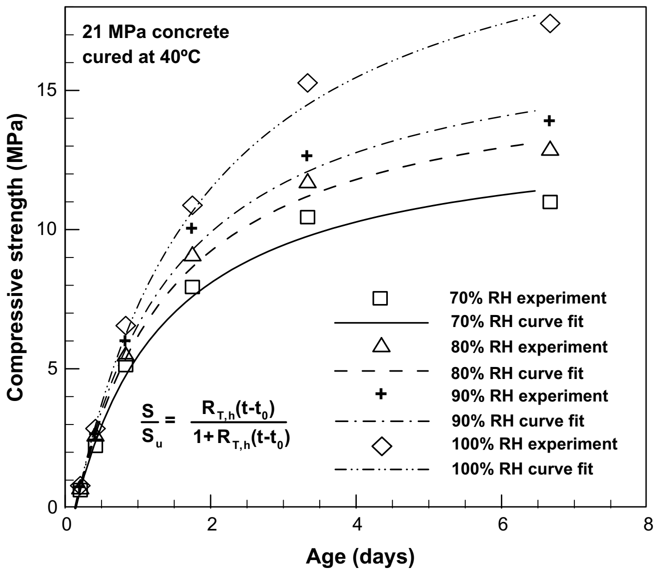

Fig. 2. Compressive strength data for concrete cylinders cured at 40 °C and different humidities.

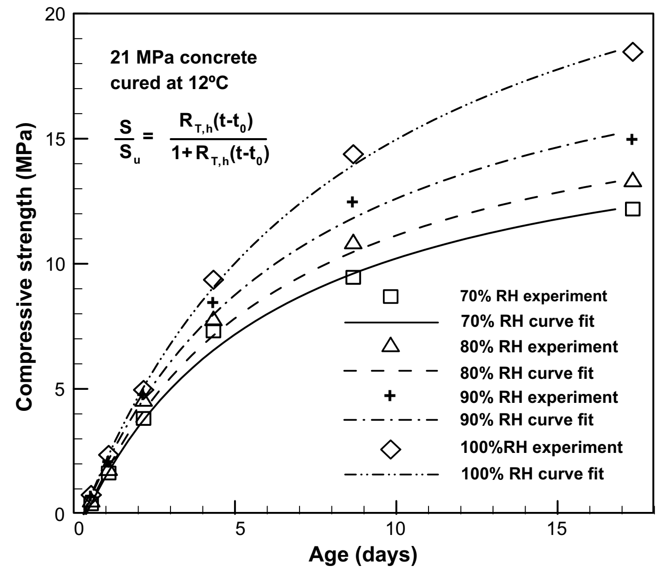

Fig. 4. Compressive strength data for concrete cylinders cured at 12 °C and different humidities.

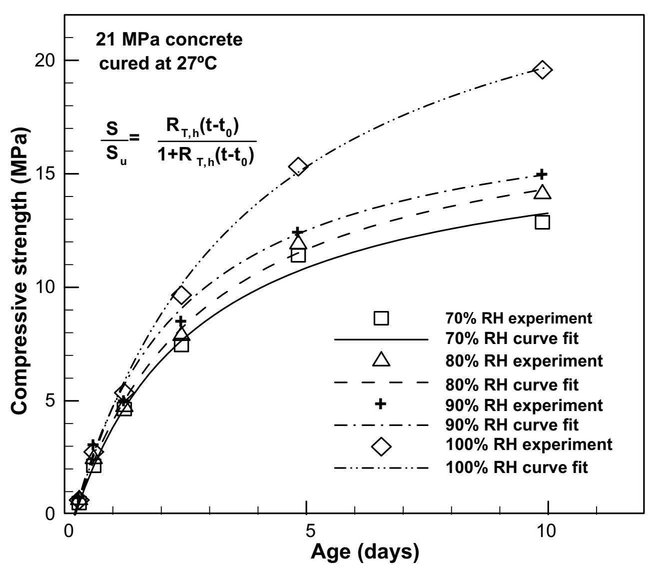

Fig. 3. Compressive strength data for concrete cylinders cured at 27 °C and different humidities.

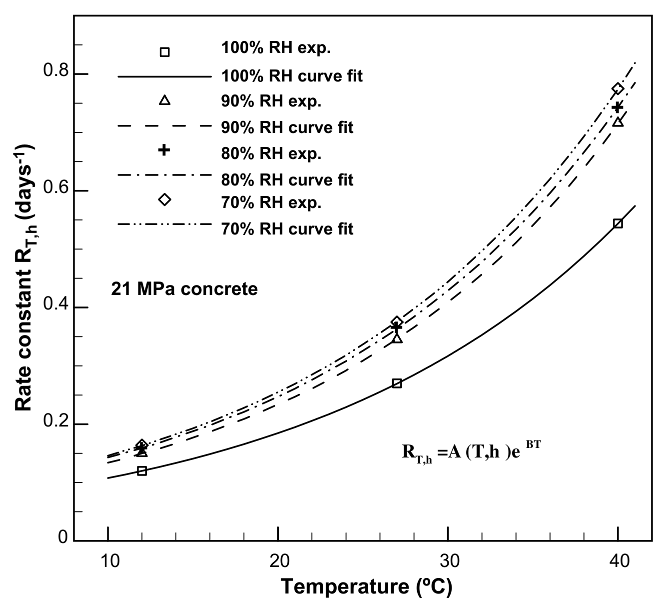

Fig. 5. The rate constants $R_{T,h}$ for concrete cured at different humidities.

of J_h as a function of the relative humidity is accurately fitted by a reverse hyperbolic curve as shown in Fig. 6. The regression limiting J_u, humidity rate constant k_h, and initial humidity constant h_0 are given in Table 7. The average value of h_0 is −5.12% RH for this 21 MPa concrete mixture. For other concrete mixtures, 35 MPa and 56 MPa, which are not shown in this paper, the variations of h_0 with temperatures were also small. The limiting J_u is a linear function of curing temperature and can be expressed as

$$J_u = C \cdot T + D \tag{11}$$

with $C = 0.0009586$ 1/°C, $D = 1.4624$ and $R^2 = 0.998$. If T_r is set as 27 °C, then the limiting humidity factor at reference temperature is $J_{ur} = 1.4883$, and the corresponding humidity rate constant $k_{h_r} = 0.400(\%\mathrm{RH})^{-1}$ using Eq. (4). The humidity-adjusted rate constant at T_r and h_r can be calculated from Eq. (9) as $R_{T_r,h_r} = 0.27801/^\circ\mathrm{C}$ which is same as the rate constant k_r at the same reference temperature and 100% RH applying the regression constants listed in Table 5.

The humidity-adjusted equivalent age t'_e can be obtained by employing Eqs. (6) and (7). It is noted that J_u in Eq. (6) is a linear function of curing temperature as indicated in Eq. (11). Therefore this humidity-adjusted affinity ratio considers not only the curing temperature effect but also the influence of relative humidity on the strength development of concrete cylinders.

Table 5
The regression constants A and B for 21 MPa concrete cylinders $R_{T,h} = A(T,h) \cdot e^{(B \cdot T)}$

Humidity	100% RH	90% RH	80% RH	70% RH	Average
A (days^{-1})	0.06277	0.07649	0.08228	0.08388	–
B (1/°C)	0.05397	0.05587	0.05502	0.05557	0.05511

Table 6
Humidity factors for 21 MPa concrete cylinders

T_c (°C)	Humidity (% RH)	$R_{T,h}$ (days^{-1})	J_h
40	100	0.5435	1
	90	0.7156	1.3167
	80	0.7420	1.3653
	70	0.7753	1.4266
27	100	0.2697	1
	90	0.3450	1.2791
	80	0.3646	1.3519
	70	0.3753	1.3916
12	100	0.1199	1
	90	0.1497	1.2483
	80	0.1590	1.3259
	70	0.1636	1.3639

The relative strength gains for concrete cylinders cured at 70% and 80% RH, and 90% and 100% RH in the calibration test are shown in Figs. 7 and 8, respectively. The symbols represent the experimental data from the calibration tests, while the solid line employs Eq. (8) with $R_{T_r,h_r} = 0.27801/°C$ for this 21 MPa concrete mixture. Typical values of the humidity-adjusted equivalent ages t'_e and the predicted relative strength S/S_u for the 80% RH case are listed in Table 8. It is evident that the relative strength gain between the experimental data and theoretical prediction is less than 8% in most cases except for specimens with ages less than 2× final setting time (see the percent error column in Table 8). If only the temperature history at the center of a concrete cylinder was used, i.e., the humidity was assumed as 100% RH, then the strength gain for the 80% cured case can be yielded from the TC method as shown in the last column of Table 8. Compared to the experimental strength data listed in Table 3, it is evident that the TC method will overestimate the strength gain of a concrete cylinder cured under insufficient moisture supply in most cases. It is noted that the concrete specimens were cured at room temperature/humidity first, and then moved to a temperature/humidity chamber after the setting time. Difference between the room temperature/humidity and designed curing temperature/humidity might cause larger compressive strength error in the first two days in some cases.

In the calibration test the limiting S_u for each curing condition is well defined as listed in Table 4, since the curing temperature and humidity were kept as constant as possible. In converting the humidity-adjusted equivalent age t'_e, the curing temperature and

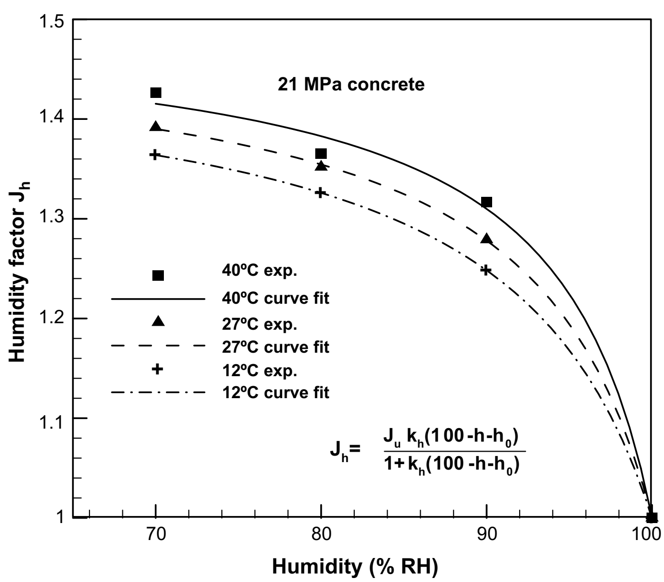

Fig. 6. The humidity factors J_h for concrete cured at different humidities.

Table 7
Humidity rate constants for concrete specimens

Type (MPa)	Temperature (°C)	J_u	k_h (% RH^{-1})	h_0 (% RH)	Average h_0 (% RH)
21	40	1.5004	0.4877	−4.1	−5.12
	27	1.4890	0.4011	−5.1	
	12	1.4736	0.3433	−6.15	
35	40	1.9899	1.6838	−0.60	−0.50
	27	1.9592	1.8956	−0.55	
	12	1.9313	3.0680	−0.35	
56	40	1.8579	0.3885	−3.00	−2.67
	27	1.8365	0.4598	−2.60	
	12	1.7047	0.5915	−2.40	

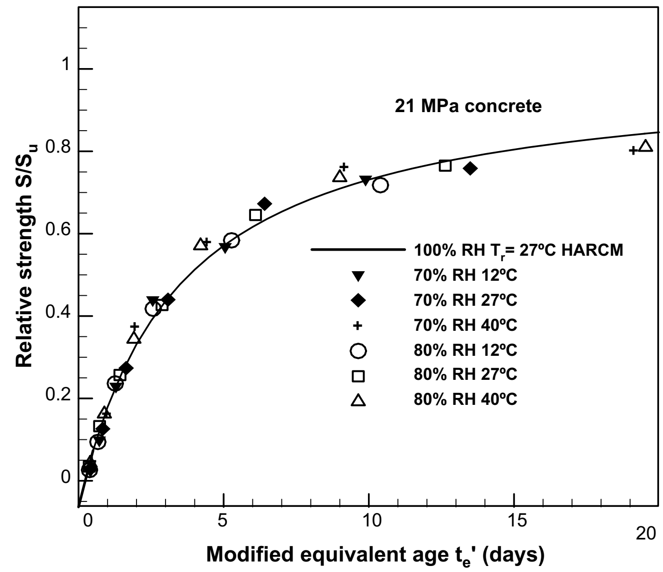

Fig. 7. The relative strength gains for concrete specimens cured at 70% and 80% RH.

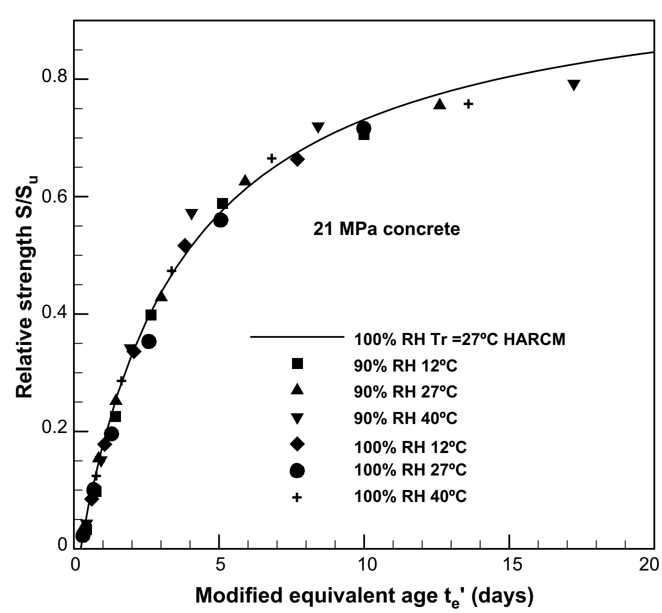

Fig. 8. The relative strength gains for concrete cylinders cured at 90% and 100% RH.

Table 8
The predicted strengths for 21 MPa concrete cylinders cured at h = 80% RH

Curing temperature (°C)	Age t (days)	t'_e (days) HARCM	S (MPa) HARCM	S/S_u (1) (expected)	S/S_u (2) (prediction)	Absolute difference (1)–(2)	Percent error $\frac{(1)-(2)}{(1)} \times 100\%$	S (MPa) TC method
12	0.542	0.378	0.48	0.026	0.043	−0.0171	−65.38	0.52
	1.083	0.667	1.75	0.094	0.112	−0.0173	−19.15	2.02
	2.167	1.267	4.51	0.244	0.226	0.0176	7.38	4.65
	4.333	2.572	7.73	0.418	0.396	0.0218	5.26	8.88
	8.667	5.271	10.80	0.584	0.584	−0.0005	0.09	14.06
	17.333	10.402	13.28	0.718	0.739	−0.0212	−2.92	18.74
27	0.302	0.370	0.72	0.035	0.039	−0.0040	−11.29	0.42
	0.604	0.717	2.22	0.132	0.122	0.0100	7.58	2.19
	1.208	1.430	4.74	0.257	0.252	0.0045	1.95	5.19
	2.417	2.881	7.87	0.427	0.426	0.0011	0.23	9.51
	4.833	6.101	11.90	0.645	0.621	0.0247	3.72	14.84
	9.667	12.632	14.11	0.765	0.775	−0.0101	−1.31	19.51
40	0.208	0.401	0.68	0.043	0.049	−0.0065	−13.95	0.47
	0.417	0.893	2.58	0.162	0.159	−0.0161	1.85	2.58
	0.875	2.016	5.46	0.344	0.334	−0.0171	2.91	6.17
	1.667	4.209	9.05	0.571	0.526	0.0560	7.88	10.36
	3.333	9.001	11.68	0.736	0.709	0.0248	3.67	14.78
	6.667	19.531	12.84	0.810	0.843	−0.0332	−4.07	18.13

relative humidity records during each time interval are necessary. Since the humidities in the calibration tests are programmed in advance, only a constant humidity value is substituted into Eq. (6). Fig. 9 depicts the temperature histories for concrete cured at 70% and 80% RH during the calibration test. It is noted that if the concrete cylinders are cured under variable temperature and humidity, the relative strength gain S/S_u will lose its physical meaning because the denominator S_u listed in Table 4 was obtained under a constant relative humidity but variable temperature condition. This S_u is not a constant in the variable temperature/humidity environment. However, the absolute strength gain of the concrete can be yielded through Eq. (10), and will be explained in the next section.

As a summary, the data reduction for the calibration procedure can be described as follows:

(1) For concrete of the same mixture, cast concrete cylinders or mortar cubes and cure at three different temperatures (12 °C, 27 °C, 40 °C). For each temperature, the concrete cylinders are cured at four different humidities (70%, 80%, 90% and 100% RH), and are tested at six scheduled dates for the compressive strength data.

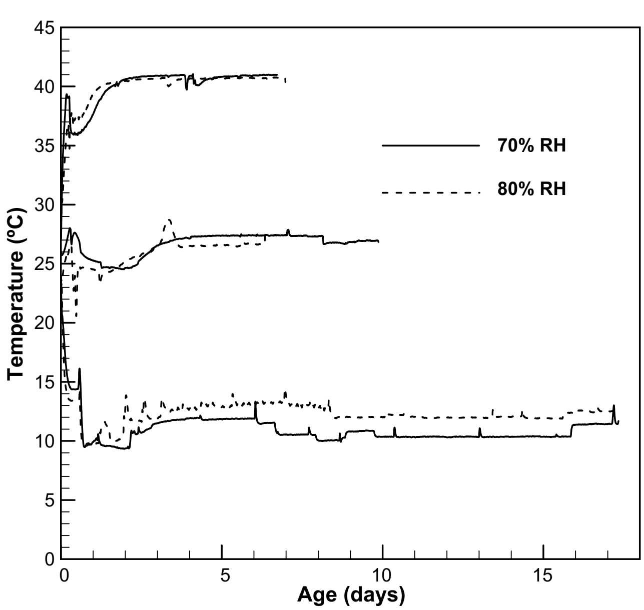

Fig. 9. Temperature histories for concrete cylinders cured at 70% and 80% RH.

(2) From the strength–age data at a fixed temperature and humidity, find the S_u, $R_{T,h}$, and t_0 following the TC method.
(3) Find the constant $A(T, h)$ and B from Eq. (1) for a fixed humidity as listed in Table 5, and the average B can be obtained.
(4) For a fixed curing temperature, calculate the humidity factor J_h as defined in Eq. (2), and tabulated in Table 6.
(5) Fit J_h with an inverse hyperbolic curve using Eq. (3) and obtain the J_u, k_h and h_0. The average h_0 can be obtained.
(6) For the J_u at different temperature, find the linear regression constant C and D from Eq. (11).

4.3. Verification of humidity-adjusted rate constant model (HARCM)

After the data reduction procedure described above, the necessary constants A_{100}, C, D, average B, R_{T_r,h_r}, average h_0, t'_{0r} and S_u to form a humidity-adjusted rate constant model are known. To examine the applicability of this model, three kinds of verification programs were conducted. The corresponding temperature and humidity records of these three programs are shown in Fig. 10. For concrete cured in outdoor water baths, the peak temperatures were due to the solar radiation at noon. For the outdoor air-dried specimens, the temperature shows variations similar to those of the second program, since both sets of specimens were cured outdoors at the same time. It is evident that during rain the temperature dropped while the relative humidity reached a plateau. Due to the variations of temperatures and humidities in these programs, the limiting strength S_u also varies with temperature and humidity. It is assumed that S_u is a bi-quadratic function of curing temperature T and humidity h as

$$S_u(T,h) = a_0 + a_1 T + a_2 h + a_3 T^2 + a_4 T \cdot h + a_5 h^2 + a_6 T^2 \cdot h + a_7 T \cdot h^2 + a_8 T^2 \cdot h^2 \quad (12)$$

By using the 12 regression values S_u (three temperatures × four humidity combinations) listed in Table 4, and a least square scheme, these coefficients were obtained as

$a_0 = -8.045$, $a_1 = 9.303$, $a_2 = 0.2466$, $a_3 = -0.1957$,

$a_4 = -0.2136$, $a_5 = 0.8623 \times 10^{-3}$, $a_6 = 0.450 \times 10^{-2}$,

$a_7 = 0.1241 \times 10^{-2}$, and $a_8 = -0.2645 \times 10^{-4}$.

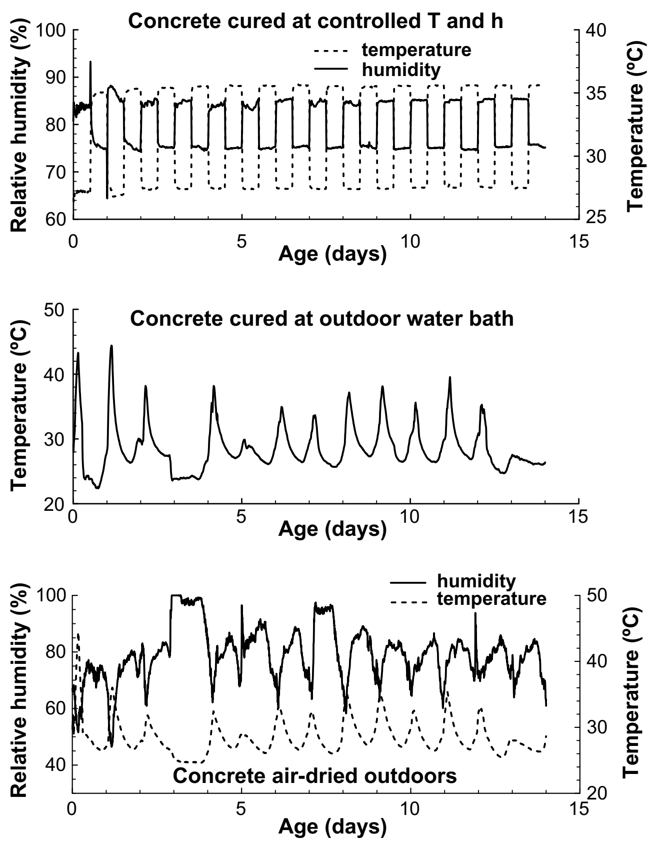

Fig. 10. Temperature and humidity history for the verification tests.

From this the S_u (in MPa) at arbitrary temperature and humidity can be interpolated. Therefore, the relative strength gains S/S_u will also exhibit some peak-trough behavior. To overcome this, an incremental form of Eq. (10) in estimating the strength gain induced by the temperature/humidity variations is adopted. Fig. 11 shows the predicted strength gains of these three verification programs, where good correlation can be seen. The difference between the experimental data and the prediction from the humidity-adjusted rate constant model is within 10% for most cases. It is interesting that for the outdoor air-dried concrete specimens, if the humidity factors were not taken into account, there would be an erroneous strength estimate as shown by the dotted line which almost coincides with outdoor water cured case. The maximum error is 49% of the TC approach compared with the experimental data. This suggests that if the concrete cylinder is cured under insufficient moisture or water supply environment, the rate constant model should consider the humidity factor to obtain a reasonable strength gain.

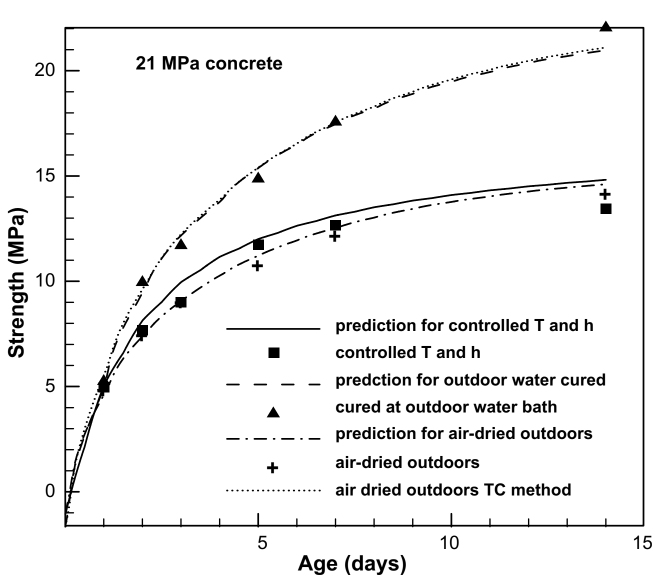

Fig. 11. The strength prediction for the verification programs.

In these three verification programs, only concrete cylinders of the same size as the calibration test were adopted, therefore the size effect of the maturity index due to different surface to volume ratio was not considered. This aspect of the maturity method needs further study. Due to the capacity of the temperature/humidity chamber, only concrete cylinders of $\phi 7.5\ \text{cm} \times 15\ \text{cm}$ were used in this study. For concrete members in which the member sizes are considerably larger than the specimens used here, the self-curing effect of the interior of the member and the internal temperature rise due to hydration should be considered as well.

5. Conclusions

In order to predict the early age compressive strength gain of concrete cylinders cured under variant temperature and humidity conditions, a humidity-adjusted rate constant model and humidity-adjusted equivalent age were developed in this study. In the calibration test, concrete specimens were cured under three different temperatures and four different humidities. From the compressive strengths at different ages the humidity influencing factor was quantified. Several verification programs for concrete cylinders cured under programmed temperature/humidity condition; cured outdoors with air dry conditions and cured in outdoor water bath were also performed to validate the applicability of this humidity-adjusted rate constant model. From this study, the following conclusions can be drawn:

1. For a specified concrete mixture, a calibration test to quantify the influence of the environmental relative humidity is needed. The procedure follows the specification as stated in ASTM C1074, however, the calibrated concrete specimens should be cured under at least four different humidities (e.g., 70%, 80%, 90% and 100% RH) for each curing temperature (e.g., 12 °C, 27 °C, and 40 °C, respectively).
2. A humidity factor J_h is introduced to evaluate the influence of humidity on the magnitude of the rate constant. Under the same curing temperature, the humidity factor J_h increased with decreasing relative humidity. This might result from the higher RH gradient between the concrete core and the ambient environment at early age.
3. The relation of humidity factor as a function of RH was accurately fitted by a reverse hyperbolic curve in this study. Since there are three parameters to be determined in a reverse hyperbolic curve, it is suggested that the concrete specimens be cured under at least four humidities if the least squares method is employed.
4. In order to estimate the in-place strength of concrete cylinders cured at arbitrary temperature and relative humidity, it is necessary to interpolate the limiting S_u obtained from the calibration tests as a function of temperature and relative humidity. An accumulative strength gain equation has been applied successfully to estimate the concrete cylinder strength development under variable temperature and relative humidity history. Verification programs show that this humidity-adjusted equivalent age and humidity-adjusted rate constant model can predict the in-place strength growth of concrete cylinders with a maximum error of 10%.

5. Application of this proposed maturity function to other concrete structures needs further study, since size effects on the internal moisture distribution and self-curing of the concrete member were not investigated.

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