- Technical Paper -

EVALUATION OF EQUIVALENT AGE CONSIDERING THE INFLUENCE OF RELATIVE HUMIDITY

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ABSTRACT

This paper proposed a new equivalent age function which allowed to calculate the equivalent age at different curing conditions of temperature(T) and relative humidity (RH). Based on the experimental compressive strength of three different size specimens at different curing condition, the proposed relative humidity influence factor is formulated. The result indicated that the experimental equivalent age increased with the increasing of curing relative humidity. Equivalent age at 100%RH exhibited much high value than that of other relative humidity. The proposed hyperbola function could precisely fit the relative humidity influence factor at different ages. By the comparison between experimental and evaluated equivalent age, it can be found that the proposed approach can effectively predict the equivalent age of each size.

Keywords: equivalent age, temperature, relative humidity, specimens size

1. INTRODUCTION

The maturity method is a technique to account for the combined effects of time and temperature on the compressive strength development of concrete. It could be considered as a medium that links the cement reaction degree to compressive strength. The maturity rule presented by Saul [1] stated that concrete samples of the same mixture had approximately the same strength at the same maturity. Freiesleben Hansen and Pedersen [2] proposed a new function to calculate the maturity index from the temperature history during curing based on the Arrhenius function that was applied for describing the effect of temperature on the rate of a chemical reaction. This new method allows to compute the equivalent age of concrete. Therefore, the practical curing age of concrete samples is able to be converted to the equivalent age at a reference temperature of 20ºC.

However, the generally used maturity method only involves the relationship between temperature and curing age. Most of the researches neglect the influence of relative humidity during the prediction of strength development. Relative humidity, as one of the main curing factors not only in laboratory experiment but also in practical construction, has a direct effect on cast-in-place concrete. Relative humidity shows a significant factor on describing the properties of cementitious production such as shrinkage and creep. As for the strength evaluation of early age concrete, it is essential to assess the initial degree of hydration. Hydration of cement-based materials generally involves many complex processes, which are influenced by several factors, such as mineral admixture types, w/c ratio, temperature, relative humidity (RH), etc. However, the influence of humidity on cement performance is usually neglected by researchers. Indeed, the ambient humidity has significant influence on cement hydration. Some research has revealed that cement hydration stops if humidity is below 80% [3-5]. Jenson [6] reported that the limiting value of humidity for hydration of alite, belite and tricalcium aluminate were 85%, 90% and 60%, respectively. Therefore, in the curing process of concrete, it is necessary to consider the influence of environmental relative humidity on its strength development, in terms of the equivalent age development.

However, in previous studies about the maturity method [7-11], only the temperature-time dependent effect is considered as a variable to compute the maturity of concrete. The effect of relative humidity on maturity is barely mentioned. In view of the importance of relative humidity for hydration and strength growth, this article proposes a new parameter of humidity influence factor g_{RH} onto the equivalent age function to describe the humidity effect. Experimental work applied on the compressive strength of cement mortar samples which curing at different curing condition of various temperatures and relative humidities. To explain the humidity effect on different depths of samples, three sizes of samples were utilized in this paper. Through regression analysis, the expression of g_{RH} was calculated and the experimental and evaluated values of equivalent age has been discussed.

2. TEST PROGRAMS

2.1 Method introduction

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Based on the compressive strength evaluation function according to fib Model Code for Concrete Structures 2010[7], a temperature-relative humidity influenced equivalent factor $t_{e_{T,RH}}$ is proposed to instead the original equivalent age factor t_e that only demonstrated the temperature dependence. A conversion operation is performed on the fib Model code 2010, and the equivalent age is allowed to be calculated as follows.

$$t_{e_{T,RH}} = \frac{28}{\left\{1 - \frac{\ln[f_{cm}(t)/f_{cm}]}{s}\right\}^2} \quad (1)$$

Where,

$f_{cm}(t)$: the mean compressive strength in MPa at an age t in days;

f_{cm}: the mean compressive strength at the age of 28 days according to curing T and RH;

s: a coefficient which depends on the strength class.

In this research that considering the influence of relative humidity, f_{cm} is defined as the mean compressive strength at the age of 28 days of reference temperature 20 ºC and reference relative humidity 100%; s is a coefficient which depends on the strength class of cement ranging from 0.20 to 0.38 [12]. Here, the value of s is taken 0.31 by referring to the notice of the Ministry of Land, Infrastructure, Transport and Tourism, Japan [13] which gives the value of ordinary Portland cement (OPC) that used in the present research.

The modified equivalent age ($t_{e_{T,RH}}$) considered the effect of both temperature (T) and relative humidity (RH) is proposed as,

$$t_{e_{T,RH}} = \sum_{i=1}^{n} \Delta t_i \, exp\left[13.65 - \frac{4000}{273+T(\Delta t_i)}\right] \cdot g_{RH} \quad (2)$$

Where,

Δt_i: the number of days where a temperature-relative humidity prevails;

$T(\Delta t_i)$: the mean temperature in ºC during the time period of Δt_i

g_{RH}: nondimensional relative humidity factor on the modified equivalent age.

Consequently, $t_{e_{T,RH}}$ can be obtained from Eq. (1) and Eq. (2) by introducing the test result of compressive strength of concrete at various levels of temperature (T) and relative humidity (RH). Since the curing with 100%RH was considered as a standard condition in previous research, a modification procedure should be performed on the calculation of g_{RH} to make it equal to 1.0 when RH is 100%. Therefore, relative humidity factor g_{RH} is suggested to be calculated as,

$$g_{RH} = \frac{t_{e_{T_f,RH}}}{t_{e_{T_f,RH_r}}} \quad (3)$$

Where,

$t_{e_{T_f,RH}}$: the equivalent age for the curing condition of a fixed temperature T_f and an arbitrary relative humidity RH;

$t_{e_{T_f,RH_r}}$: the equivalent age for the curing condition of a fixed temperature T_f and reference relative humidity RH_r ($RH_r = 100\%$).

It is also revealed that the development tendency of g_{RH} versus relative humidity (RH) can be accurately fitted to the modified hyperbola function as,

$$g_{RH} = \frac{RH}{100+k(RH-100)} \quad (4)$$

Where,

RH: the environmental curing relative humidity;

k: the rate coefficient of curing relative humidity.

Table 1 Properties of cement and sand

Ordinary Portland Cement (OPC)		Sand	
Density (g/cm^3)	1.41	Absolutely density (g/cm^3)	2.54
Specific surface area (cm^2/g)	3340	Surface dry density (g/cm^3)	2.59
Initial setting time (min)	135	Absorption (%)	2.03
Final setting time (min)	200	Fineness modulus	2.65

Table 2 Mix proportion

W/C	Unit Weight (kg/m^3)		
	Water	Cement	Sand
0.5	282.3	564.6	1552.7

Table 4 Regression result of k

Size	1 day	3 days	7 days	28 days
1cm	0.289	-3.314	-7.268	-24.850
5cm	0.134	-1.560	-5.159	-22.841
10cm	-0.305	-1.953	-2.161	-13.654

2.2. Experimental investigation

Ordinary Portland cement, produced by a local company of Taiheiyo cement corporation, is used as the only cementitious materials in the mixing process. River sand is utilized as the fine aggregate. Main property of used cement and sand is included in Table 1. Cement mortar specimens with mass ratio of water : cement = 0.5 : 1 was applied for the compressive strength test, more details of mix proportion are shown as Table 2. Three different size of cement mortar specimens (cubic sample with side length of 1cm, cylindrical sample with ø5×10cm and ø10×20cm,) were applied for the compressive strength test in the current research to contrast the effect of relative humidity on different size of cement mortar. For the curing program, cement mortar specimens of each sizes were cured in the constant temperature and relative humidity curing chamber with three different temperature (10ºC, 18ºC and 40ºC) and four different relative humidity (70%, 80%, 90% and

Table 3 Experimental compressive strength

Size	T (ºC)	RH(%)	Compressive strength (MPa)				f_{cm}
			1 day	3 days	7 days	28 days	
1 cm^3	10	70	2.90	4.04	5.20	6.81	
		80	3.27	5.72	6.50	8.96	
		90	3.35	5.99	9.89	15.03	
		100	3.91	13.61	21.34	30.06	32.72
	18	70	9.35	17.42	18.10	21.45	
		80	10.35	18.55	22.88	28.88	
		90	10.63	19.66	27.26	33.00	
		100	11.05	22.78	29.25	40.26	40.88
	40	70	16.19	20.81	21.34	22.87	
		80	17.57	22.20	25.16	29.11	
		90	17.58	24.13	26.97	32.23	
		100	19.66	27.81	32.81	39.97	35.83
ø5×10cm	10	70	1.44	8.14	9.67	10.17	
		80	2.14	9.58	12.45	12.80	
		90	2.51	10.88	13.76	17.18	
		100	3.00	13.05	22.61	34.88	37.74
	18	70	6.08	15.87	20.32	24.54	
		80	6.91	17.44	24.26	29.70	
		90	7.28	18.35	27.38	33.20	
		100	7.92	21.48	31.30	40.96	41.26
	40	70	15.79	20.01	21.81	23.72	
		80	16.10	21.37	27.39	30.11	
		90	16.68	23.49	29.47	33.77	
		100	17.95	27.63	32.99	40.44	36.79
Ø10×20cm	10	70	1.72	8.11	14.78	18.18	
		80	2.54	8.68	15.88	20.76	
		90	3.23	9.13	16.88	23.37	
		100	3.55	13.40	22.44	34.51	37.34
	18	70	5.25	15.51	24.26	29.79	
		80	6.32	16.11	26.08	32.91	
		90	6.32	18.02	27.63	34.79	
		100	7.72	19.87	29.01	40.86	41.15
	40	70	12.49	18.95	24.53	25.57	
		80	13.69	20.05	27.41	31.74	
		90	14.38	22.14	29.07	33.97	
		100	16.81	27.38	32.90	40.17	36.55

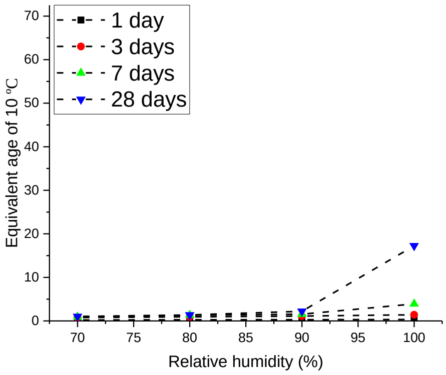
100%). After mixing, the specimens are directly moved to the corresponding curing condition and demolded after curing 9-12 hours depending on setting of cement mortar. Water bath curing is considered as 100% relative humidity at each temperature during the experiment. For each compressive test, average test value of three specimens were adopted as the compressive strength value as each test ages (1 day, 3 days, 7 days and 28 days) according to the standard of JIS A1108.

Compressive strength of 1cm^3 cube specimens was measured by using the testing machine of model AGS-X-5KN and that of ø5cm and ø10cm specimens were tested with high rigidity compression testing machine of model CCH-3000KN both produced by Shimadzu Co. Ltd. Three different sizes are expressed as 1cm, 5cm and 10cm for simply in this research.

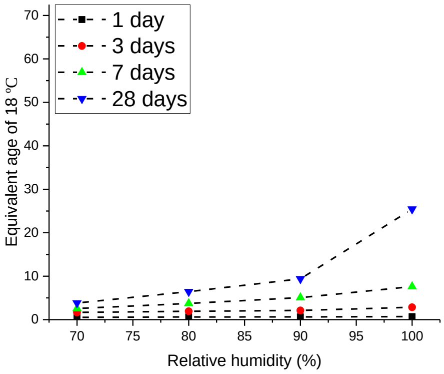
3. RESULT AND DISCUSSION

3.1 Experimental equivalent age

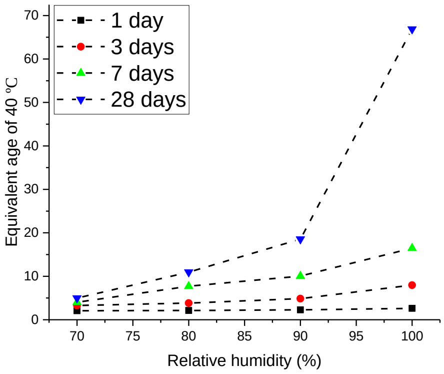
In terms of the description of the above section, compressive strength and calculated f_{cm} of different specimens sizes at curing condition and ages are shown in Table 3. By referring Eq. (1), the equivalent age $t_{e_{T,RH}}$ in this research is allowed to be calculated by using the experimental compressive strength $f_{cm}(t)$ and f_{cm} of the 28-days compressive strength at 20 ºC and 100% RH. Fig. 1 shows the equivalent age of different relative humidities and curing ages at the temperature of 10ºC, 18 ºC and 40 ºC. It is apparent that temperature plays an important role on the magnitude of equivalent age.



a. Experimental equivalent age at 10 ºC



b. Experimental equivalent age at 18 ºC



c. Experimental equivalent age at 40 ºC

Fig. 1 Experimental equivalent age at different curing temperature of 5cm specimens

Equivalent ages at high temperature are much higher than that at low temperature. For example, the equivalent age of 28-days at 40ºC and 100%RH is 66.87 days (see Fig. 1(c)). This is much higher than it at 18ºC and 10 ºC of 100%RH, which exhibited the equivalent age of 25.43 days and 17.26 days respectively, shown as Fig. 1 (b) and (a). The equivalent age increases with the increase of relative humidity, especially at the curing age of 28 days. At low relative humidity, the results of equivalent ages corresponding to different curing ages are very close. With the development of relative humidity, this difference of equivalent age becomes more noticeable. Since the equivalent age is calculated based on the 28-days compressive strength at the reference temperature of 18 ºC and the relative humidity of 100%RH, it shows a significantly low value at 10 ºC. At an unsaturation of relative humidity condition, the equivalent ages don't show a large change. However, at 100%RH especially at the 28 days of 100%RH, the equivalent age increased rapidly.

3.2 Regression analysis

Through a series of calculation by Eq. (1) and Eq. (2), relative humidity factor g_{RH} can be obtained by introducing the experimental compressive strength. Considering that the influence factor temperature and relative humidity work independently in Eq. (2). Hence, temperature is considered as non-effect on the relative humidity factor g_{RH} in this research. Before the operation of Eq. (3), the calculated g_{RH} is averaged at each curing temperature.

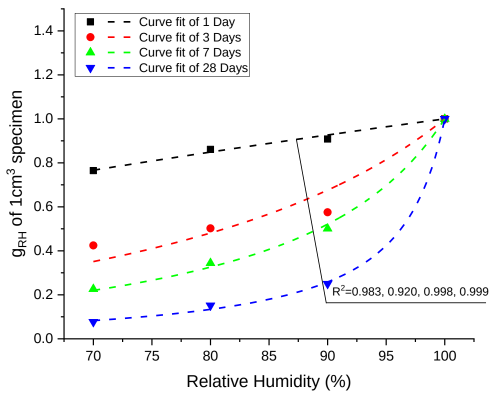
Regression result of each sizes specimens are plotted in Fig. 2 and the value of parameter k is included in Table 4. It is easy to find that the proposed humidity influence expression of Eq. (4) has shown a good consistency with the fitting curve, especially in the smaller size specimens of 1cm and 5cm. Almost all the R^2 are above 0.95 except the one of 1cm and 10cm specimens at curing age of 3 days, which R^2 are 0.920 and 0.894. The regression results of rate coefficient k and curing age show an inverse relationship, and the value of k decreases as the number of days increases. Since k is defined as rate coefficient of relative humidity, which indicates the sensitivity of relative humidity variable on the development of g_{RH}. It also could be found in Table 4, at 7 and 28 days, k shows a higher value with bigger size specimens. Such regular tendency couldn't be found in early curing ages of 1 and 3 days. Because at the initial stage of curing, external humidity will not affect the hydration process of the specimen due to the existence of sufficient internal moisture. Therefore, the k value is not very regular in the early age. On the other hand, from the view of regression process, the relatively low R^2 at 3 days also influenced the accuracy of regression result k.

Considering that the humidity rate coefficient k expresses the rate of ambient relative humidity effect. It should be a variable with time that shows the different impact at different stage of curing. A linear relationship can be found by contrasting value of k with curing time. Which can be expressed as Eq. (5).

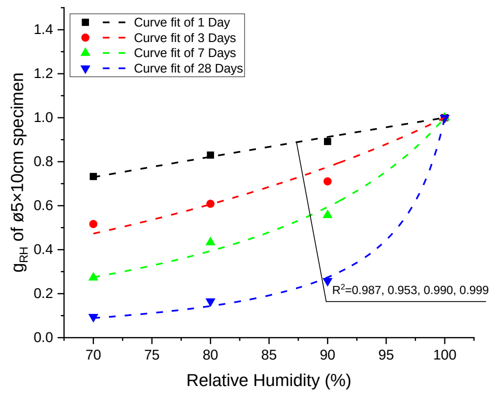
$$k = a * t \quad (5)$$

Where, a is a fitting parameter.

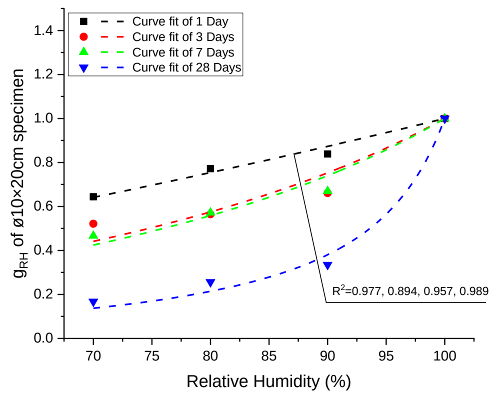
In terms of the description of the above section, compressive strength and calculated f_{cm} of different specimens sizes at curing condition and ages are shown in Table 3. By referring Eq. (1), the equivalent age $t_{eT,RH}$ in this research is allowed to be calculated by using the experimental compressive strength $f_{cm}(t)$ and f_{cm} of the 28-days compressive strength at 20 ºC and 100% RH. Fig. 3 shows the linear fitting of rate coefficient k at different curing ages by referring Eq. (5). The corresponding fitting results of a are -0.897, -0.807 and -0.479 of specimen size of $1cm^3$, ø5×10cm and ø10×20cm, respectively. According to Fig. 3, k is shown as a linear function within high agreement with



a. g_{RH} of 1cm^3 size specimens



b. g_{RH} of ø5×10cm size specimens



c. g_{RH} of ø10×20cm size specimens

Fig. 2 Curve fitting to determine parameter k

curing ages. As for the slop of parameter a, the 1cm and 5cm size specimens show a similar result of -0.897 and -0.807. Which is higher than the one of 10cm size specimens with the value of -0.479. This means the bigger the specimen is, the lower the influence of experimental relative humidity is. It is also distinct that the coefficient is a function of specimen size. As the increase of specimen sizes, the a-value increases. This tendency also can be found within a relationship of linear

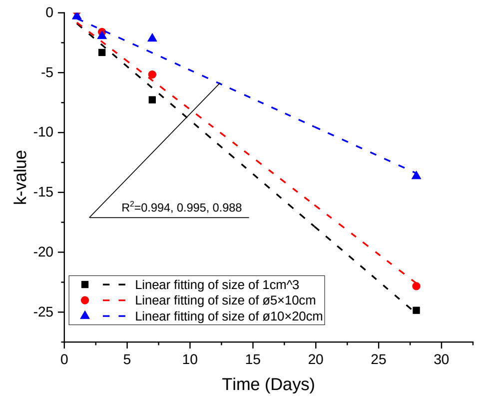


Fig. 3 Linear fitting of rate coefficient k

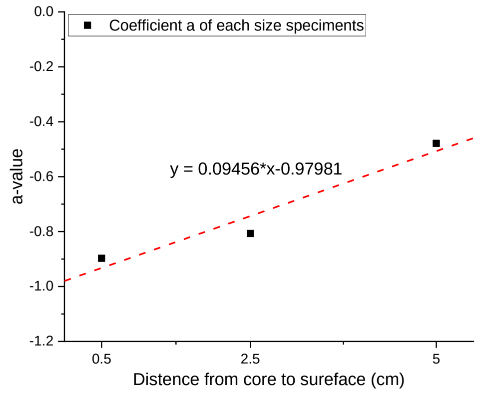


Fig. 4 a of different size

form, which is shown as Fig. 4. It is noted that the x-aixs adopts the distance from the specimen core to the specimen surface.

3.3 Verification program

Through the introduction of the above section, the proposed relative humidity influence factor g_{RH} is able to be expressed by introducing the relative humidity history during curing into equation. The relative humidity modified equivalent age $t_{e_{T,RH}}$ of Eq. (2) is able to be computed as the follows.

$$t_{e_{T,RH}} = \sum_{i=1}^{n} \Delta t_i \, exp\left[13.65 - \frac{4000}{273+T(\Delta t_i)}\right] \cdot \frac{RH_i}{100+k(RH_i-100)} \quad (6)$$

Where,

RH_i : the mean relative humidity during the time period of Δt_i

The comparison between experimental and evaluated equivalent age of different size specimens at different relative humidity are plotted in Fig. 5. The agreement between evaluated value and experimental value of equivalent age at each size specimens are higher. The Pearson correlations coefficients of 1cm, 5cm and 10cm specimens are 0.992, 0.988 and 0.992, respectively.

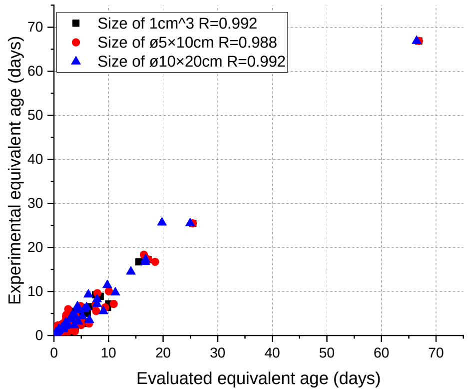


Fig. 5 Comparison between experimental and evaluated equivalent age

Main reason leads the low precision of evaluation of 5cm specimens is that the calculated results of relative humidity influence factor g_{RH} at different temperature exhibits a relatively larger error range based on the measured compressive strength. Theoretically, temperature and relative humidity act respectively referring Eq. (2) and Eq. (6) onto equivalent age, therefore, the procedure of taking the average value of g_{RH} at three applied temperature leaded to a low accuracy.

Evaluated results of different relative humidity also show a different accuracy related to the experimental results of equivalent age. Evaluated value of equivalent age at 100%RH show a high correspondence with the experimental value. Which is the original equivalent age expression without the influence of relative humidity. Because the calculating procedure has been considered to make g_{RH} equals 1 at 100%RH at each temperature and curing ages.

4. CONCLUSION

Based on the fib model code for concrete construction 2010, a relative humidity modified equivalent age function has been proposed. The experimental result of equivalent ages of different temperature and relative humidity and curing ages were obtained through the strength evaluation function. By means of the regression analysis, the proposed relative humidity coefficient of three different size specimens was formulated. The result can be summarized as follows.

(1) The experimental equivalent age increases with the increase of relative humidity. Low equivalent age was shown at low temperature of 10 ºC, even at a later curing age of 28 days. At an unsaturation of relative humidity condition, the equivalent ages don't show a large difference, however, it increased rapidly at 100%RH and 28 days.

(2) The proposed hyperbola function could adapt to the experimental results of relative humidity influence factor effectively. The fitting results of 1cm and 10cm were better than it of 5cm specimens.

(3) The proposed function can evaluate the equivalent age development accurately, especially of the smaller size specimens of 1cm and 10cm.

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