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Long-term strength prediction of concrete with curing temperature

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Abstract

This paper describes a new strength time temperature prediction equation, which utilizes curing temperatures to improve the accuracy of estimates of long-term strength. To develop the model equation, existing data reported in the literature were collected and used. The data were converted into a relative strength ratio based on the strength at 28 days for 8 average curing temperatures in a range of $-0.6 \sim 59.7$ °C. The effect of the diffusion shell, which happens during cement hydration, on the long-term strength as a function of the curing temperature was considered using the rate constant model. Temperature influence factors such as rate constant, limiting strength, and reaction coefficient, which are functions of curing temperature, were incorporated in the new equation. Verification of the proposed model was performed by regression analysis.

The results of regression analyses showed that the proposed model has higher reliability than existing model equations. The proposed model has higher accuracy at long-term ages the difference with existing models at an early age is not significant.

Keywords: Curing; Temperature; Long-term performance; Compressive strength; Concrete

1. Introduction

Over the past several decades, many researchers have investigated the combined influence of time and curing temperature on the compressive strength development of concrete. In 1951, Saul [1] introduced the well-known maturity concept systematizing the effect of curing temperature on concrete compressive strength. Maturity accounts for the combined effects of time and temperature on strength gain and is evaluated from the in-place temperature history of the concrete. Rastrup [2] converted maturity into equivalent age, by Arrhenius equation [3], etc. The effect of curing temperature on the concrete compressive strength decreases with increasing age; however, maturity is a value which is independent of age. To solve these problems, various relationship equations between maturity and strength, such as the logarithmic model of Plowman [4] and the parabolic model of Carino [5] have been suggested.

Tank and Carino [6] proposed a rate constant model, which represents curing temperature as a rate constant using hydration theory of the concrete. Rate constant and strength can be determined simultaneously from regression analyses on experimental data of concrete strength obtained under various isothermal curing conditions. To improve the accuracy of strength prediction at early ages, Kim et al. [7] suggested an equivalent age model considering the influence of curing time data points after evaluating the existing rate constant model.

Chengju [8], Kjellsen and Detwiler [9], and Carino [10] noted that existing model equations can only be applied to the age less than 28 days and are not applicable for ages greater than 28 days. Klieger [11] and Price [12] experimentally investigated the effect of initial curing temperature on long-term strength. Kjellsen and Detwiler [9]

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showed that existing model equations are not adequate for predicting the long-term strength.

In this study, the authors suggest a new strength prediction equation, which can predict more accurately the effect of curing temperature on the long-term strength of the concrete. The suggested equation used a rate constant model [6] and considered the diffusion shell effect, which influences diffusion and penetration of the hydrate. In addition, temperature influence factors with curing temperature were also considered. The curing temperature conditions of existing data used for regression analyses include eight temperatures (−0.6, 5.1, 11.3, 22.2, 31.7, 41.6, 49.2, and 59.7 °C). The cements used in the experiments were Portland cements (ASTM Type I and III) and fly ash cement.

2. Maturity and strength characteristics of concrete

2.1. Maturity

Maturity used for strength prediction of the concrete is defined as the product of temperature function and time. It is based on the summation of the temperature histories and can be written as

$$M = \int_0^t H(T)\mathrm{d}t \tag{1}$$

where M is the maturity at age t, $H(T)$ is the maturity temperature function, T is the curing temperature: and dt is the time interval. Saul [1] stated the principle of the maturity concept as, "Concrete of the same mixture at the same maturity has approximately the same strength whatever combination of temperature and age goes to make up that maturity".

Sometimes maturity is represented as an equivalent age, which accounts for the combined effects of time and temperature on strength development. Equivalent age represents the age at a reference curing temperature T_r that would result in the same fraction of the limiting strength as would occur from curing at other temperatures. The concept of equivalent age can be written as

$$t_e = \frac{\int_0^t H(T)\mathrm{d}t}{H(T_r)} \tag{2}$$

where t_e is the equivalent age.

Equivalent ages of maturities suggested by Saul [1] and based upon the Arrhenius equation by Freiesleben and Pedersen [3] may be expressed as Eqs. (3) and (4), respectively.

$$t_{es} = \frac{\sum (T - T_o)\Delta t}{(T_r - T_o)} \tag{3}$$

$$t_{ea} = \sum \exp\left[\frac{E}{R}\left(\frac{1}{T_r + 273} - \frac{1}{T + 273}\right)\right]\Delta t \tag{4}$$

where t_{es} and t_{ea} are the equivalent ages of the Saul model and the Arrhenius equation, respectively; T_o is the datum temperature; E is the activation energy (kJ/mol); and R is the universal gas constant (8.3144 J/mol K).

2.2. Compressive strength of concrete

To predict the compressive strength of concrete with curing temperature, a relationship between strength and maturity is necessary. Plowman [4] expressed the relationship between strength and maturity by Saul as a natural logarithmic function as follows:

$$S_p = a + b\log M_s \tag{5}$$

where S_p is the strength prediction value by Plowman equation; M_s is the maturity by Saul model and a and b are constants.

In 1956, Bernhardt [13] showed that the relative strength development ratio of concrete is proportional to the size of the unhydrated portion of the concrete and introduced a rate constant k as a proportional constant when cement is hydrated. He suggested the strength increasing rate with age of the concrete as follows:

$$\frac{\mathrm{d}(S/S_u)}{\mathrm{d}t} = k(1 - S/S_u) \tag{6}$$

where S is the compressive strength of concrete at age t; S_u is the limiting strength; k is the rate constant influenced by curing temperature.

The hydration of cement occurs primarily by chemical reaction between water and cement on the surface cement particle, and, secondarily, it happens by the diffusion and penetration of the hydrate. However, Eq. (6) disregards this secondary phenomenon. Since the cement particle reacts with water and the hydrate on the surface cement particle acts as a shell against diffusion of the hydrate, continuous increase of the strength is retarded. To consider the effect of the diffusion shell, Bernhardt [13] suggested the following empirical Eq. (7).

$$\frac{\mathrm{d}(S/S_u)}{\mathrm{d}t} = k(1 - S/S_u)^2 \tag{7}$$

Strength development of concrete starts at a fixed time after placement of concrete. However, it is generally noted that the long-term strength is not affected by the starting time of strength development. Accordingly, if the hardening is assumed to begin just after placement as a boundary condition, the concrete strength prediction equations of Eqs. (6) and (7) can be written as Eqs. (8) and (9), respectively.

$$S = S_u[1 - \exp(-kt)] \tag{8}$$

$$S = \frac{S_u kt}{1 + kt} \tag{9}$$

In Eqs. (8) and (9), which are strength prediction equations by the rate constant model, rate constant k and limiting strength S_u can be obtained from regression analyses of experimental data on compressive strength of concrete specimens cured under isothermal condition. Where rate constant and limiting strength can be changed with curing temperature.

Carino [14] suggested Eq. (10) under the assumption that the hardening of concrete starts not at concrete placement time but at time t_o.

$$S = \frac{S_u k(t - t_o)}{1 + k(t - t_o)} \tag{10}$$

where t_o is the age in days when strength development is assumed to begin.

3. Development of a long-term strength prediction model with curing temperature

3.1. Effect of diffusion shell with curing temperature

The variations of strength with curing temperature of the concrete are mainly caused by changes of the cement paste composition. Changes of the composition occur due to physical effects of the curing temperature of concrete and by the shell's retarding effect on the diffusion of the hydrate in the secondary reaction of cement hydration [9,10,15]. Physical effects are caused by the difference of relative volume expansion. Water and void volumes within the concrete increase with an increasing curing temperature. When the initial stress resulting from this phenomenon is higher than the tensile strength, microcracks form and/or coalesce, voids increase, and the strength of concrete decreases. Due to this problem, long-term strength decreases with an increase in initial curing temperature [10,16,17]. When the curing temperature is high, the hydration velocity increases and stiffer and thicker hydrate shells are formed around the cement particles. This shell plays a retarding role for diffusion of cement particles. Bernhardt and Carino assumed that the retarding effect on diffusion of hydrate shells is uniform regardless of curing temperature. However, the composition of cement paste and the effect of diffusion shell, which influences diffusion of the hydrate can change with the curing temperature [8,18–20].

3.2. New rate constant model

The increasing rate of concrete strength can be shown as Eq. (11) using strength function and rate constant.

$$\frac{dS}{dt} = f(S) \times k \tag{11}$$

where dS/dt is the increasing rate of the strength; $f(S)$ is the function of strength.

In this study, in order to consider the effect of diffusion shells described in the previous section, a reaction coefficient (r), which is a function of the curing temperature, was introduced. In Eqs. (6) and (7), the reaction coefficients were 1.0 and 2.0, respectively. From existing research, the coefficient is known to be a constant and independent term regardless of curing temperature. Accordingly, if the reaction coefficient becomes a function of curing temperature, the effect of the curing temperature on the diffusion and penetration affecting the secondary reaction of cement can be considered. For an isothermal curing condition, the strength function can be illustrated using the reaction coefficient as follows:

$$f(S) = S_u \left[1 - \left(\frac{S}{S_u}\right)\right]^r. \tag{12}$$

After substituting Eq. (12) for $f(S)$ of Eq. (11), the following integral equation (13) under the boundary condition in which the strength development of concrete starts just after placement can be obtained.

$$\int_0^s dS \Big/ \left[1 - \frac{S}{S_u}\right]^r = S_u \int_0^t k dt \tag{13}$$

After integrating Eq. (13) independently of curing temperature, the strength equation can be expressed as Eq. (14) under isothermal curing condition (i.e., constant concrete curing temperature of T).

$$S_T(t) = S_{uT}\left\{1 - \frac{1}{[1 + (r_T - 1)k_T t]^{\frac{1}{r_T - 1}}}\right\} \tag{14}$$

where S_{uT}, k_T, and r_T are the limiting strength, the rate constant, and the reaction coefficient, respectively, at curing temperature T. Eq. (14) is a parabolic equation having an initial slope of $k_T \cdot S_{uT}$ and converging to the limiting strength S_{uT}.

To accurately predict the strength of concrete with curing temperature using Eq. (14), the changes of rate constant, limiting strength and reaction coefficient with curing temperature should be determined. Data obtained from the literature and age-strength tests of concrete specimens cured isothermally under various temperatures in the laboratory were used. The influence factors were obtained from the regression analysis of experimental data.

4. Comparison of the proposed model equation and existing experimental data

4.1. Regression analyses

To verify the strength prediction equation with curing temperature, regression analyses on experimental data collected with various curing temperatures were performed. The accuracy of the proposed equation was confirmed by calculating the correlation coefficient (R^2). The correlation coefficient was obtained from a linear relationship equation between values from the proposed equation and experimental data.

To evaluate the change of the reaction coefficient with the curing temperature, experimental data on curing temperatures of −0.6 °C [21,22], 5.1 °C [7,9–11,23], 11.3 °C [9,11,22–24], 22.2 °C [7,9–11,21–25], 31.7 °C [9–11,23], 41.6 °C [7,9–11,21,23–25], 49.2 °C [9–11,25], and 59.7 °C [25] were collected and rearranged with average curing temperatures. In this study, the number of data points for curing temperatures of −0.6, 5.1, 11.3, 22.2, 31.7, 41.6, 49.2, and 59.7 °C were 9, 9, 18, 23, 10, 20, 9, and 3, correspondingly. The best prediction equation with curing temperature of the existing model equations was found to be Eq. (9). Regression analysis results using Eqs. (9) and (14) with curing temperature are shown in Fig. 1(a) to (h). Additionally, each factor's values obtained from regression analyses are given in Table 1. In Table 1, P.M. and B.M. mean temperature influence factors are, respectively, calculated using Eq. (14) suggested in this study and using Bernhardt's parabolic model equation (Eq. (9)).

As can be seen from Fig. 1, the difference between the proposed model and Bernhardt's parabolic model equation

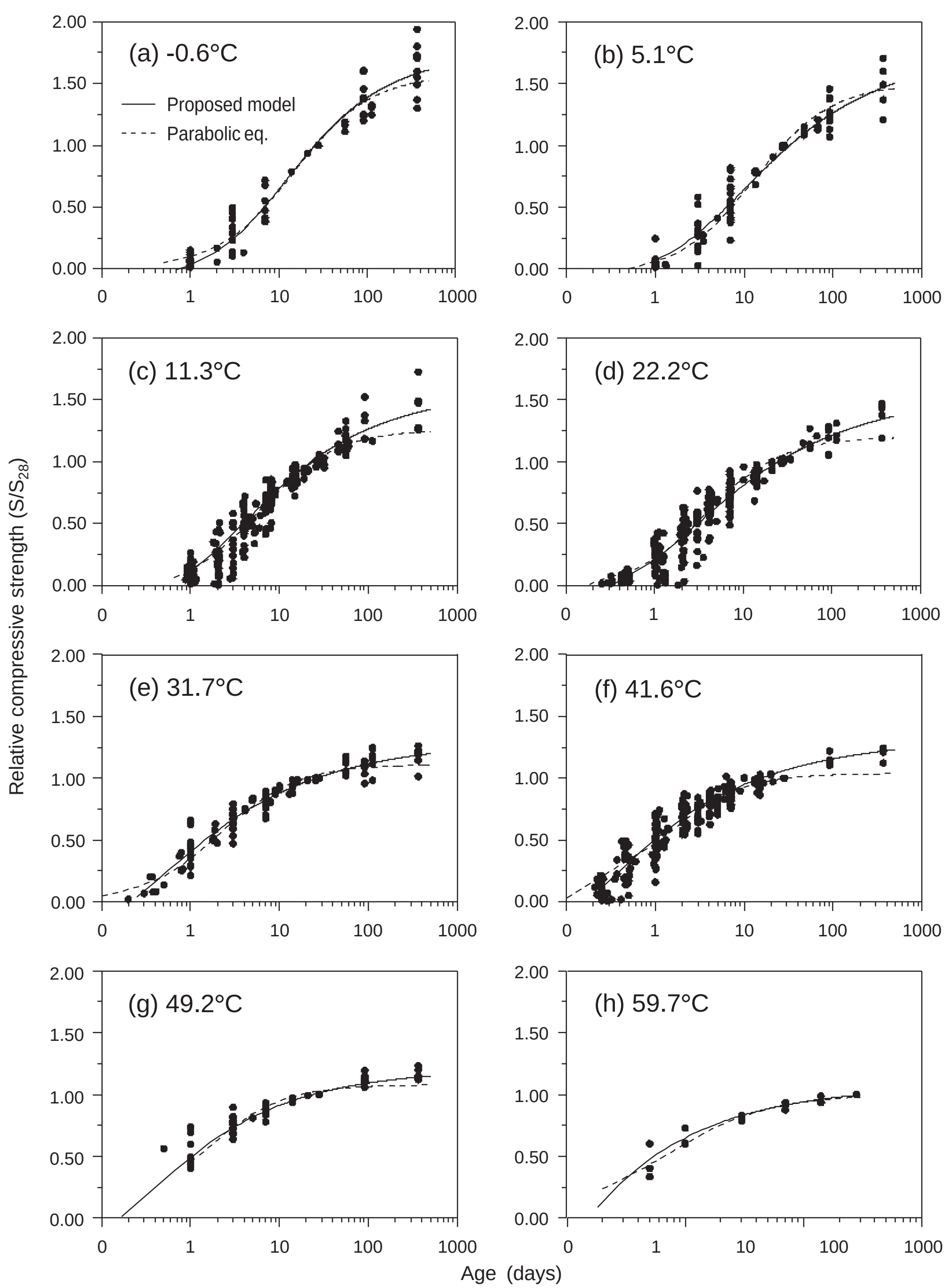

Fig. 1. Regression results of the model proposed in this study and Bernhardt's parabolic equation with data from Refs. ([7,9], etc.).

Table 1
Regression analysis results for temperature influence factors of the proposed model and parabolic equation

Curing temperature (°C)		Rate constant (k)	Limiting strength/strength at 28 days (S_u/S_{28})	Reaction coefficient (r)	Correlation coefficient (R^2)
−0.6	P.M.	0.0670	1.76	2.58	0.94
	B.M.	0.0570	1.64	2.00	0.93
5.1	P.M.	0.0799	1.56	2.43	0.91
	B.M.	0.0793	1.46	2.00	0.90
11.3	P.M.	0.1423	1.44	2.66	0.90
	B.M.	0.1431	1.29	2.00	0.89
22.2	P.M.	0.2654	1.35	2.91	0.93
	B.M.	0.2521	1.19	2.00	0.91
31.7	P.M.	0.5439	1.25	3.14	0.93
	B.M.	0.4524	1.10	2.00	0.91
41.6	P.M.	0.7942	1.22	3.02	0.91
	B.M.	0.7342	1.07	2.00	0.90
49.2	P.M.	1.0586	1.22	3.39	0.93
	B.M.	0.7144	1.08	2.00	0.92
59.7	P.M.	2.0280	1.11	2.92	0.92
	B.M.	1.6571	1.01	2.00	0.91

P.M. and B.M. mean temperature influence factors are respectively calculated using Eq. (14) suggested in this study and using Bernhardt's parabolic model equation (Eq. (9)).

is insignificant for up to 7 days. However, the proposed equation predicts the experimental data well after 28 days. Therefore, if the reaction coefficient is assumed to be a constant with the curing temperature (such as Bernhardt [13] and Carino [14]), it is noted that the effect of initial curing temperature on long-term strength is not well represented. This is similar to the research results reported by Chengju [8] and Kjellsen and Detwiler [9].

4.2. Determination of temperature influence factors

In Table 1, it is noted that temperature influence factors are written as a function of curing temperature. The reaction coefficient, which considers the influence of the diffusion shell, shows inconsistent trends with increasing curing temperature. Namely, the effect of curing temperature on diffusion reaction of cement hydrate is not uniform.

Rate constant can be a function of curing temperature and be written in the form of either the Saul model or the Arrhenius equation. The Saul model has long been used because of its simplicity. The Arrhenius equation is known to clearly represent the influence of curing temperature. Eqs. (15) and (16) show rate constants as a function of curing temperature after carrying out regression analyses using the Saul model and the Arrhenius equation, respectively, on rate constant values obtained by Carino's parabolic model equation.

$$k_{\text{Saul}}(T) = 0.0156(T + 10) \quad (15)$$

$$k_{\text{Arrh}}(T) = 8.41 \times 10^6 \exp\left(\frac{-5142}{T + 273}\right) \quad (16)$$

where k_{Saul} and k_{Arrh} are the rate constants by the Saul model and the Arrhenius equation, respectively. In Eq. (15), a datum temperature of −10 °C was used. Correlation coefficients of Eqs. (15) and (16) are 0.73 and 0.96, respectively. From this, it is noted that the rate constant is more accurate when the influence of curing temperature is represented as the Arrhenius equation.

Using a similar procedure to obtain Eqs. (15) and (16), the rate constants obtained by Eq. (14) proposed in this study can be represented as the following equations (Eqs. (17) and (18)), where correlation coefficients of Eqs. (17) and (18) are 0.73 and 0.99, respectively.

$$k_{\text{Saul}}(T) = 0.0193(T + 10) \quad (17)$$

$$k_{\text{Arrh}}(T) = 1.80 \times 10^7 \exp\left(\frac{-5311}{T + 273}\right). \quad (18)$$

When rate constants obtained from the parabolic model equation and the proposed model are represented as the temperature function by the Saul model, correlation coefficients are equal. When represented as a temperature function by the Arrhenius equation, however, the correlation coefficient was somewhat improved. When the parabolic model equation and the proposed model are represented as a temperature function of the Arrhenius equation, activation energies were 42.17 and 44.32 kJ/mol, respectively. When activation energy is available, curing temperature can be converted into maturity or equivalent age, and the activation energy changes largely with type and properties of cement. Generally, the activation energy has a value of 30~50 kJ/mol. However, to date, studies have not adequately considered how variations in the mixing environment, such as the water–cement ratio, mixture condition, and so on, effect the activation energy. Fig. 2(a) shows the relationship between the rate constant by equations (Eqs. (17) and (18)) and curing temperature. From this figure, it is noted that the rate constant varies not as a linear equation with curing temperature like the Saul model, but as an exponential function like the Arrhenius equation.

To determine the variation of limiting strength with curing temperature, regression analyses using an equation suggested by Gardner [22] were performed. The results are shown in Fig. 2(b). Correlation coefficient of Eq. (19) is 0.97.

$$S_{\text{uj}}(T) = 0.16 S_{28} \exp\left(\frac{637}{T + 273}\right) \quad (19)$$

where S_{uj} is the limiting strength by Jalali and Abyaneh. From Fig. 2(b), it is noted that the limiting strength decreases with increasing curing temperature.

Fig. 2(c) shows the variation of the reaction coefficient with curing temperature. Reaction coefficient increases with increasing temperature; however, the increasing rate decreases as temperature continues to increase. Accordingly,

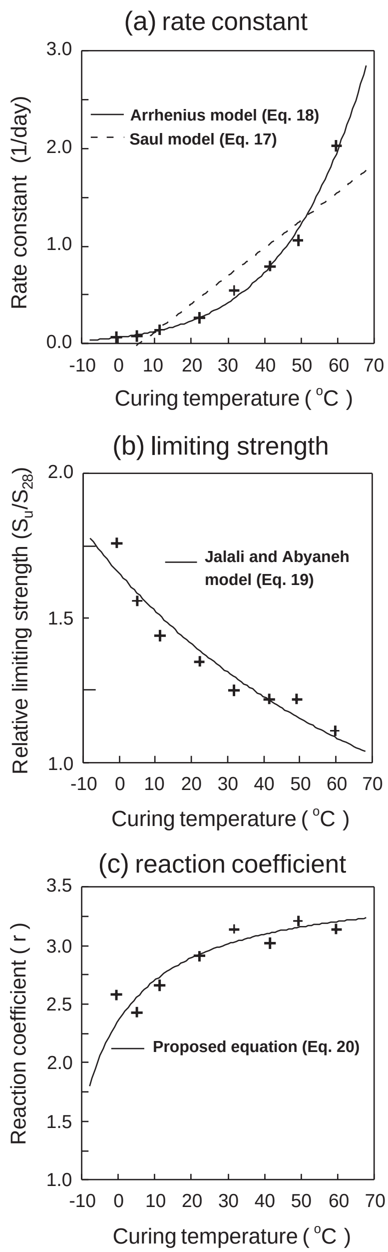

Fig. 2. Variation of temperature influence factors with curing temperature.

the reaction coefficient can be represented as an exponential function equation, and the regression results on each averaged curing temperature are shown in Eq. (20). Correlation coefficient of Eq. (20) is 0.98.

$$r(T) = 3.55\exp\left(\frac{-8.17}{T+50}\right). \tag{20}$$

4.3. Comparison of strength prediction equations

To compare the proposed equation and existing model equations, the curing temperature was changed to the equivalent age by the Saul model and the Arrhenius equation, and the values were applied to each model.

Kim et al. [7] improved the equivalent age equation from the existing Saul model and Arrhenius equation and suggested, by experiments, a more accurate equivalent age equation for the case where the curing temperature is high at an early age. However, the data used in this study were obtained from tests carried out under isothermal curing and the focus put on long-term strength prediction. According to the study of Kim et al. [7], the rate constant and limiting strength at an early age change with data points of curing time. After 7 days, however, the influence of curing time data points was minor. Thus, in this study, the effect of curing time data points on the long-term strength prediction after 28 days was not considered in calculating the equivalent age.

First, comparison of existing models and the proposed equation was performed using equivalent age by the Saul model. Age with each averaged curing temperature can be convertible to equivalent age using the Saul model of Eq. (3) for a reference temperature 20 °C and datum temperature −10 °C. Eqs. (21)–(24) are, correspondingly, regression analysis results using the Plowman model (Eq. (5)), the exponential model (Eq. (8)), the Bernhardt's parabolic equation (Eq. (9)), and the equation suggested in this study (Eq. (14)).

$$S = S_{28}[0.5466 + 0.3159\log(t_{es})] \tag{21}$$

$$S = S_u[1 - \exp(-0.1420t_{es})] \tag{22}$$

$$S = S_u\left(\frac{0.2211t_{es}}{1+0.2211t_{es}}\right) \tag{23}$$

$$S = S_u\left(1 - \frac{1}{(1+0.4575t_{es})^{0.60}}\right). \tag{24}$$

Eq. (21) and Eqs. (22)–(24) represent each strength prediction equation in terms of relative strength based on the strength at 28 days and the limiting strength, respectively. Fig. 3 shows the comparison of the suggested model and existing model equations when the Saul model is used in calculating the equivalent age. Here, to efficiently compare the effect of curing temperature on the long-term strength of concrete, experimental data after 7 days were used. From this figure, the strength prediction equation, which is proposed in this study, based on Saul and Plowman model for the equivalent age produced more accurate results than the existing prediction equations.

Eq. (4) can also be used to obtain the equivalent age using the Arrhenius equation. Eqs. (16) and (18) were used to calculate activation energies of the parabolic and proposed model equations. Regression analysis results of parabolic and suggested model equations using the equi-

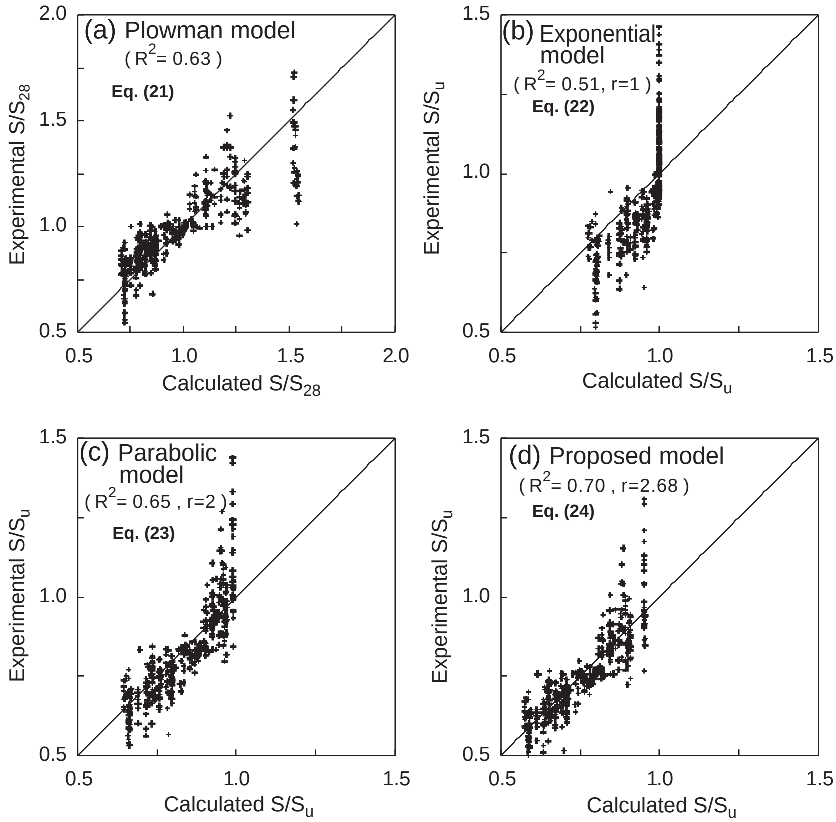

Fig. 3. Comparison of experimental data and prediction values by the proposed model and existing models with Saul's equivalent age.

valent age calculated by the Arrhenius equation are given in Eqs. (25) and (26), respectively.

$$S = S_u \left(\frac{0.2265 t_{ea}}{1 + 0.2265 t_{ea}} \right) \tag{25}$$

$$S = S_u \left(1 - \frac{1}{(1 + 0.4649 t_{ea})^{0.51}} \right). \tag{26}$$

Eqs. (25) and (26) represent the strength in terms of relative strength based on the limiting strength. Here, the reaction coefficient of the existing parabolic model (Eq. (25)) is 2.0 regardless of curing temperature. It is also noted that the equation suggested in this study produces more accurate results at higher ages compared to the existing strength prediction equation. Strength prediction equations (Fig. 4) from the equivalent age obtained using the Arrhenius equation reflected more accurately the influence of curing temperature on the equivalent age, and the reliability of strength prediction was improved compared to the case (Fig. 3) using the Saul model. However, at longer-term ages the reliability did not improve. This is because the existing maturity concept was proposed to evaluate the influence of temperature before 28 days and the rate constant primarily affects the strength increase at an early age.

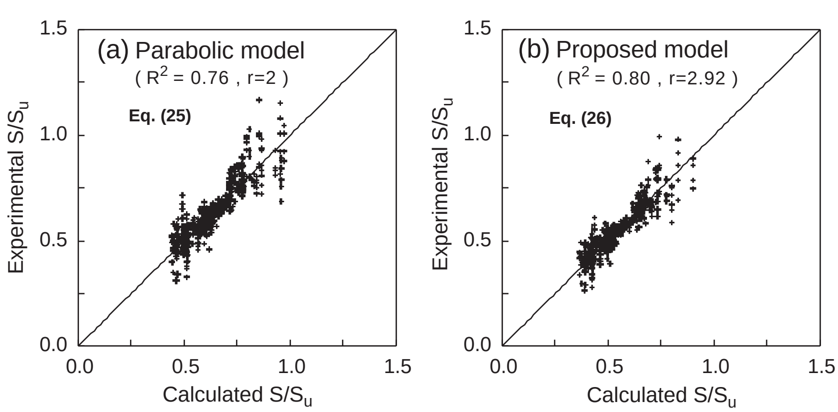

Fig. 4. Comparison of experimental data and prediction values by the proposed model and parabolic equation with the equivalent age of Arrhenius's equation.

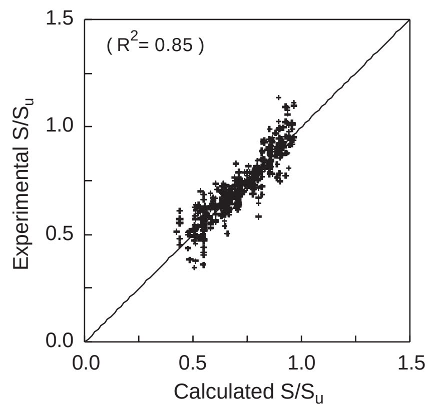

Fig. 5. Comparison of experimental data and prediction values by the proposed model (Eq. (14)) with temperature influence factors (Eqs. (18)–(20)).

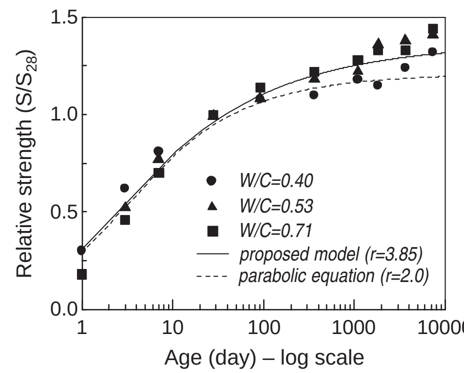

Fig. 7. Regression analyses on Wood's experimental data from 1 day to 34 years.

Fig. 5 shows the comparison of experimental data and prediction values of long-term strength by the proposed model (Eq. (14)) with temperature influence factors (Eqs. (18)–(20)). In this figure, long-term strength as a function of curing temperature is represented in terms of relative strength based on the limiting strength. In Figs. 3 and 4), the reaction coefficient with curing temperature is a constant. Accordingly, the reliability of the long-term strength prediction was not improved. From Fig. 5, however, it is noted that the variation in strength prediction decreases distinctly with age increase, especially, at a greater age. The correlation coefficient of Fig. 4(a) by Eq. (9), which is well-known as an existing model having a high accuracy, is 0.76. When the equivalent age by the Arrhenius equation is used and the reaction coefficient is constant (i.e., 2.92), the correlation coefficient is 0.80. However, the model equation with temperature influence factors proposed in this study has a correlation coefficient of 0.85. Therefore, the accuracy of long-term strength prediction was considerably improved. From this, it is noted that, to obtain a more accurate long-term strength prediction, it is necessary to consider the temperature influence factors with the curing temperature and diffusion shell effect.

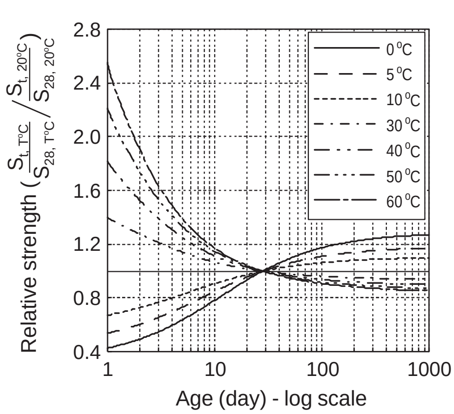

Fig. 6. Relationship between relative strength and age at various curing temperatures.

Fig. 6 shows the relationship using equations between relative strength and age considering the proposed model and temperature influence factors under the conditions of a reference temperature of 20 °C and age of 28 days. From this figure, it can be concluded that early age strength and long-term strength of the concrete increase and decrease, respectively, with increasing curing temperature.

4.4. Check of reaction coefficient using Wood's data

Fig. 7 shows regression analysis results obtained using Wood's compressive strength data [26] of the concrete from 1 day to 34 years. Experimental data were obtained from concrete specimens cured under the standard curing temperature, and in the regression analysis based on Bernhardt's parabolic equation, the reaction coefficient was 3.85. From this figure, it is concluded that existing Bernhardt's and Carino's models, which use the parabolic equation and have a reaction coefficient of 2.0, underestimate the long-term strength of the concrete. From this, it can be concluded that, to obtain more accurate long-term strengths, reaction coefficient should be a function of curing temperature and not a constant. Wood's research results show a similar pattern to this study.

5. Conclusions

In this study, the effect of curing temperature on the long-term strength of concrete was examined. The conclusions obtained from this study can be summarized as follows:

(1) When the curing temperature of concrete changes, the composition of the hydrate changes. Accordingly, this change influences the diffusion and penetration of the hydrate related to the medium- or long-term strength of the concrete. A new strength prediction equation considering diffusion and penetration of the hydrate

and temperature influence factors with curing temperature is proposed.

(2) From regression analysis, it was found that the reaction coefficient increases with increasing curing temperature. The diffusion and penetration of the hydrate gradually increases with increasing curing temperature.

(3) Using the proposed equation, regression analyses on existing test data were performed in a range of $-0.6 \sim 59.7$ °C curing temperatures. The reliability of the proposed equation was higher than existing model equations. The difference between the proposed and existing models, at an early age, was not significant, but, the accuracy of the proposed model at a long-term age, especially after 28 days, was improved.

6. Notation

a, b	Constants
dt, Δ	Time interval
E	Activation energy (kJ/mol)
$H(T)$	Maturity temperature function
k	Rate constant
k_{Saul}, k_{Arrh}	Rate constant by the Saul model and the Arrhenius equation, respectively
M	Maturity at age t
M_{s}	Maturity by Saul model
r	Reaction coefficient
R	Universal gas constant (8.3144 J/mol K)
R^2	Correlation coefficient
S	Compressive strength of concrete at age t
S_{p}	Strength prediction value by Plowman equation
S_{u}	Limiting strength
S_{uj}	Limiting strength by Jalali and Abyaneh
$S_{\mathrm{u}T}$, k_T, r_T	Limiting strength, the rate constant, and the reaction coefficient, correspondingly, at curing temperature T
t	Age
t_{e}	Equivalent age
t_{es}, t_{ea}	Equivalent ages of the Saul model and the Arrhenius equation, respectively
t_{o}	Age when strength development is assumed to begin
T	Curing temperature
T_{o}	Datum temperature
T_{r}	Reference temperature

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