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COMPRESSIVE STRENGTH DEVELOPMENT OF CONCRETE WITH DIFFERENT CURING TIME AND TEMPERATURE

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ABSTRACT

In this experimental and analytic research, the strength development for various curing histories was investigated with particular regard to the influences of curing time points with given temperatures. For this purpose, four different points of curing time were considered with an individual interval of 24 h. Two different temperatures of 5°C and 40°C were applied for the selective intervals, whereas the rest period days were under the reference curing condition of 20°C. A new model for the strength prediction was suggested based on the rate constant model. In this model, the equivalent ages introduced in the Saul and Arrhenius models were modified to show the effects of curing temperature at different ages. Test results show that the concrete subjected to a high temperature at an early age attains higher early-age strength but eventually attains lower later-age strength. The concrete subjected to a low temperature at an early age leads to lower early-age strength but almost the same later-age strength. Moreover, the proposed model showed better agreement with the test results than the existing models. *© 1998 Elsevier Science Ltd*

Introduction

Over the past several decades, numerous failures of concrete structures during construction and economic pressures to accelerate construction schedules have emphasized the need to predict the early-stage strength gain of concrete. Such a prediction is of special importance for cold-weather and hot-weather concreting and for massive concrete members. In massive concrete members, the gradient of temperature between the inner part and the outer surface is large and changes with age. Thus, a reasonable evaluation of the in-place strength with age is of practical importance to control the curing temperature and, further, to make the concrete free of crack due to the thermal shrinkage.

The well-known maturity rule put forth by Saul (1) suggests that the combined effect of time and temperature on the hardening process was related to the strength development of

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concrete. Thereafter, Freiesleben and Pedersen (2) introduced the maturity function based on the Arrhenius equation to reflect accurately the influence of temperature on the rate of strength gain of concrete. In an experimental study with different curing temperatures for the first 2 h of curing, Price (3) pointed out the importance of the initial curing temperature. He reported that the concrete cured at a high temperature showed a higher strength at an early age and a lower strength after 7 days, compared to isothermally cured concrete at 20°C. McDaniel (4) and Klieger (5) also reported the influence of curing temperature at an early age on the strength development. Volz et al. (6) stated that the present maturity method does not take into account the effect of the curing temperature at an early stage. Recently, Tank and Carino (7) derived the rate constant model to take into account the effects of temperature on the strength gain of concrete. Kjellsen and Detwiler (8) developed a modified maturity model to predict later-age strength.

Despite extensive research done over the past decades, there are still several problems in quantitatively predicting the strength development at both early and later ages. Most of the theoretical expressions for the strength development of concrete were derived based on isothermal curing. But almost all concrete in practice is under variable temperature regimes, not under isothermal conditions. Therefore, the existing model can only be applied to the approximate prediction of concrete strength for a relatively little change in curing temperatures with time points of curing. In short, most of the present maturity equations have been derived based on the assumption that the effects of curing temperatures with varying time points of curing are the same. But Guo (9) suggested that the precise prediction of concrete strength with curing temperature could be made only by a function of temperature, taking into account both effects of curing temperatures at different ages.

The purpose of the present study is to investigate experimentally and to develop a new model for the prediction of the concrete strength considering the effects of varying temperatures occurring at different ages. For this purpose, two types of concrete, having w/c ratio of 0.55 and 0.35, were investigated to be cured at two curing temperatures, 5°C and 40°C. Concrete specimens were selectively cured at both elevated and low temperatures with four different time points of 24-h curing, 0th–1st, 1st–2nd, 2nd–3rd, and 6th–7th days from the start of curing, while being standard cured at a reference temperature of 20°C for the remaining days except for the selective curing days. The compressive strength of cured concrete was measured to explicate what effects selected curing time at different ages have on concrete strength. By analyzing the test results obtained in this study, a new model for strength prediction was suggested based on the rate constant model. In the model, the equivalent ages previously introduced in Saul's and Arrhenius' models were modified by taking into account both the effects of curing temperatures and curing time points on the strength with age.

Experimental Program

Mix proportions

The concrete was proportioned using w/c ratios of 0.35 and 0.55 to obtain concrete with different strengths. For the experimental concrete, the coarse aggregate was angular crushed stone with 25-mm nominal maximum size, and the fine aggregate was river sand. The specific gravity, absorption values, absolute bulk density, and fineness modulus for coarse aggregate

TABLE 1
Mix proportions.

Mix type	W/C	S/a	Unit weight (kg/m^3)				SP (%)	AE (%)
			W	C	S	G		
NSC	0.55	0.47	185	335	835	959	—	0.2
HSC	0.35	0.45	175	495	759	940	1.0	0.2

SP: superplasticizer, AE, air-entraining agent.

are 2.66, 1.27%, 1537 kg/m^3, and 7.08, and for fine aggregate are 2.65, 0.64%, 1469 kg/m^3, and 2.64, respectively. Ordinary portland cement (ASTM type I) was used. The measured values of slump and entrained air at the time of placement were 15.9, 5.4% for 0.55 w/c and 12.5, 4.3% for 0.35 w/c, respectively. The mix proportions of concrete are given in Table 1.

Preparation of specimens

The study included tests of 324 concrete cylinders that had been subjected to various temperature histories. The specimens were made using 100- × 200-mm waxed cardboard molds and compacted with an internal vibrator. Concrete mixing was accomplished in an 80-L–capacity forced-mixing type mixer. After 1 min of dry mixing with coarse aggregate, fine aggregate and cement were placed in order; water was poured into the mixer to complete the mixing for 3 min. Just after casting, the specimens were covered by a plastic sheet to prevent the hydration water from evaporating. Mixing and specimen preparation were carried out at room temperature of 20°C ± 2°C.

Curing process

After molding, all the uncovered specimens were transferred carefully to water baths maintained at the reference curing temperature of 20°C. Two different temperatures of 5°C and 40°C were taken to obtain information on how the low and high temperatures during the early ages affect the concrete strength with age. It was based on the hypothesis that traditional maturity cannot be simply summed or integrated for fluctuating curing temperatures because temperatures occurring at different ages affect the concrete strength differently. Four different individual intervals of a day were taken to apply the lowered or elevated temperatures at ages of 0, 1, 2, and 6 days from the start of curing. The specimens were transferred to temperature programmable chambers for the selective curing and transferred back to the water baths of a reference temperature after finishing the selective curing until they were tested. The temperature histories of the specimens are given in Figure 1.

Because a sudden change in temperature can cause thermal damage to the specimen, the temperature of the curing chamber was elevated or lowered gradually over 6 h, as shown in Figure 2. Temperature–time histories of representative specimens were measured by embedded thermocouples located at the center of the cylinders. A maximum deviation of 5°C above

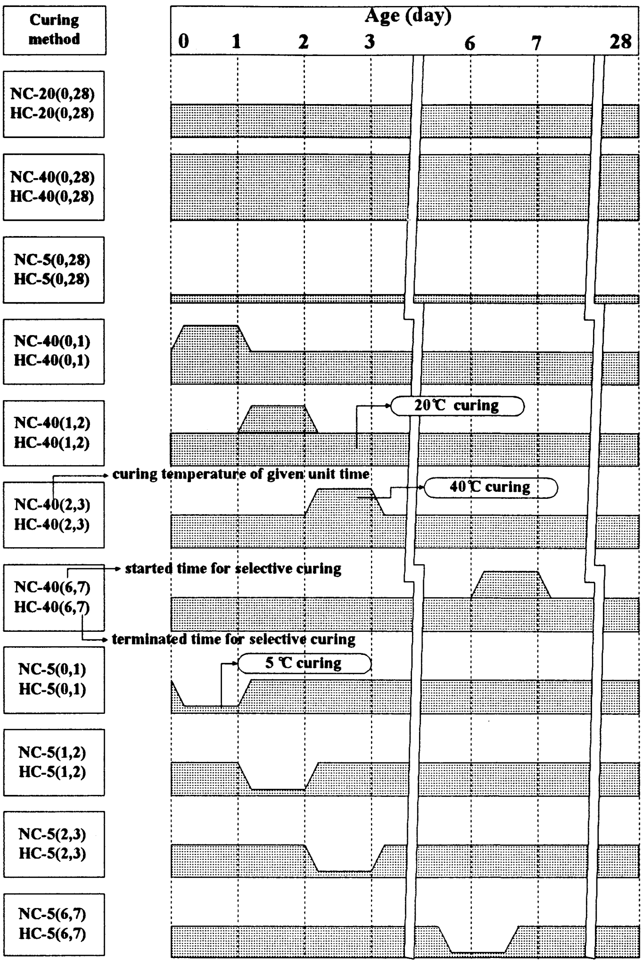

FIG. 1.
Curing histories of the specimens.

the intended curing temperature of 40°C that was observed at the age of 10 h after the start of raising temperature seems to be ascribed to the early-age heat of hydration.

Compression testing

The cylinders were stripped from their molds, and the top surfaces were ground shortly before they were tested. Compressive tests were performed at ages of 1, 2, 3, 7, 14, and 28 days using a hydraulic servocontrolled compressive testing machine with 250-ton capacity. The compressive strengths were taken as the average values of three cylinders tested.

TABLE 2
Test results.

Curing method	Compressive strength (MPa)											
	W/C = 0.55						W/C = 0.35					
	1 d	2 d	3 d	7 d	14 d	28 d	1 d	2 d	3 d	7 d	14 d	28 d
20 (0, 28)	6.96 (6.3)	12.1 (0.8)	16.4 (3.0)	25.1 (4.9)	31.7 (2.8)	35.9 (3.1)	12.2 (4.2)	24.4 (3.3)	30.9 (2.3)	39.6 (2.2)	45.5 (2.6)	49.6 (5.0)
40 (0, 1)	16.7 (3.7)	20.9 (2.7)	22.8 (1.5)	26.0 (5.1)	29.1 (5.3)	31.1 (1.4)	27.6 (2.5)	32.3 (5.8)	33.6 (3.0)	37.9 (1.8)	42.8 (1.7)	46.3 (4.1)
40 (1, 2)	—	18.3 (4.3)	22.4 (6.3)	27.4 (3.6)	30.3 (1.0)	31.9 (2.1)	—	33.2 (6.0)	35.3 (2.5)	40.7 (4.0)	43.9 (3.3)	48.2 (2.9)
40 (2, 3)	—	—	20.7 (2.9)	26.9 (2.0)	30.5 (2.7)	32.9 (3.6)	—	—	37.8 (5.3)	40.2 (2.6)	45.5 (0.8)	50.3 (2.5)
40 (6, 7)	—	—	—	25.8 (1.3)	31.6 (3.8)	33.7 (2.4)	—	—	—	40.9 (3.6)	45.3 (1.9)	51.3 (4.1)
40 (0, 28)	15.4 (2.4)	20.1 (3.1)	21.3 (3.3)	24.7 (2.7)	28.5 (6.2)	32.5 (3.0)	27.9 (5.0)	37.4 (2.7)	39.5 (2.2)	40.7 (3.1)	42.3 (2.0)	44.3 (2.2)
5 (0, 1)	0.78 (3.9)	7.16 (2.7)	12.7 (3.4)	21.7 (1.8)	26.9 (2.7)	33.5 (1.0)	3.63 (3.7)	17.8 (3.0)	27.4 (6.0)	40.4 (4.2)	46.0 (1.4)	52.4 (2.4)
5 (1, 2)	—	7.94 (1.2)	13.1 (5.1)	23.5 (1.4)	28.9 (0.9)	35.5 (1.6)	—	20.1 (2.9)	27.8 (4.5)	27.4 (3.9)	47.4 (2.7)	51.1 (1.6)
5 (2, 3)	—	—	12.8 (4.2)	23.1 (0.5)	29.5 (1.3)	34.6 (4.7)	—	—	27.7 (1.4)	39.1 (4.4)	46.6 (2.2)	51.3 (2.2)
5 (6, 7)	—	—	—	24.2 (3.8)	30.7 (2.4)	34.9 (0.9)	—	—	—	39.3 (2.7)	46.2 (4.4)	49.3 (1.6)
5 (0, 28)	0.98 (7.1)	3.14 (0.6)	5.69 (3.1)	12.9 (2.8)	18.7 (2.1)	29.9 (5.8)	4.01 (1.7)	8.53 (2.9)	13.0 (4.4)	24.3 (2.8)	33.0 (2.3)	43.2 (3.5)

Numbers within parentheses are coefficients of variation (expressed as percent) of average strength of three specimens.

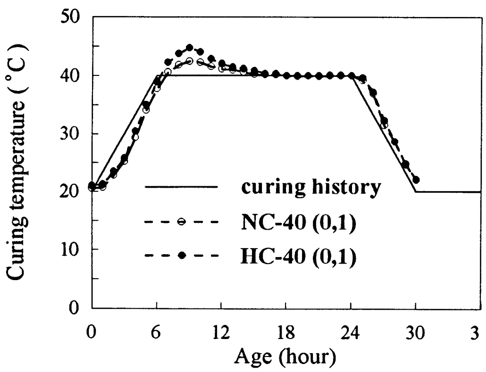

FIG. 2.
Typical temperature history for specimen NC-40(0,1).

Test Results and Analysis

Test results

The average compressive strengths at each test age for each curing condition are presented in Table 2. The strength–age data are plotted in Figures 3–5 as relative values to the strengths of isothermally cured specimens at 20°C.

The cumulative temperatures at 28 days are the same for the curing conditions, for example, as noted NC-5(t_1,t_2) or NC-40(t_1,t_2) in Figures 3 and 4. Thus, according to the traditional maturity rule, it was expected that the 28-day strengths would be the same for each group. The test data, however, show that the strength gains are different when the variable curing temperatures are applied at different ages, even with the same maturity. Figures 3 and 4 show that the concrete subjected to a high temperature at an early age attains a greater

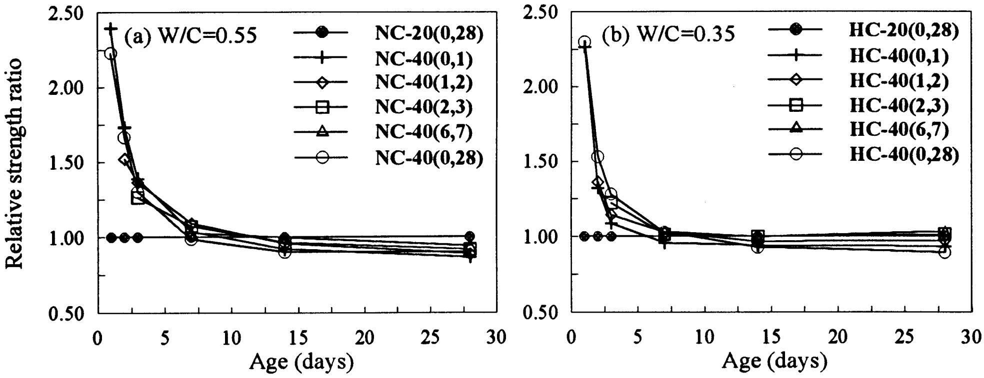

FIG. 3.
(*a*, *b*) Relative strength of selectively cured concrete at 40°C to isothermally curing at 20°C.

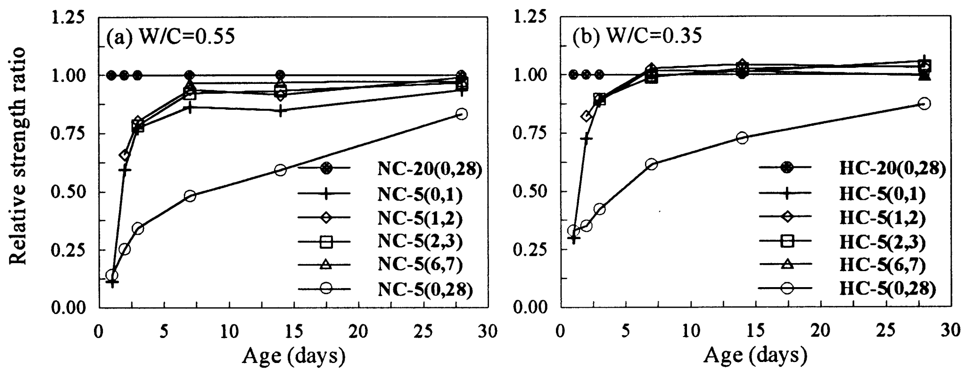

FIG. 4.
(*a*, *b*) Relative strength of selectively cured concrete at 5°C to isothermal curing at 20°C.

early-age strength but eventually attains a lower later-age strength, whereas the concrete subjected to a low temperature at an early age leads to lower early-age strength but approaches almost the same later-age strength as the isothermal cured one. Test results also show that the temperature change at ages later than 7 days has little effect on later-age strength. There was no clear deviation in this trend with different w/c ratios. Figure 5 shows the relative strength–age plot for isothermal curing at 5°C and 40°C compared to that of the isothermal curing at 20°C. In Figure 5, isothermal curing at 40°C yields a higher early-age strength but lower later-age strength, and vice versa for 5°C curing. Such a trend also was observed by Klieger (5) and Alexander and Taplin (10).

The effects of curing temperature on hydration and strength gain are still not well known. Rapid hydration due to elevated temperatures are considered to act as a “shell” that eventually hinders the diffusion of hydration products into the bulk cement paste matrix (11,12). The porosity of the bulk paste also is reported to increase as a result of nonuniform diffusion

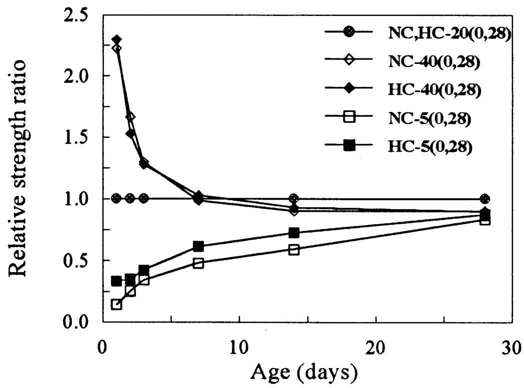

FIG. 5.
Relative strength of constantly cured concrete to isothermal curing at 20°C.

of the hydration product (13). Also, another effect may occur if the temperature is raised quickly during early ages. It may cause internal stresses exceeding the tensile strength of the immature concrete, which will lead to increased porosity and cracking and a reduced strength potential (14).

Analysis

Maturity or the equivalent ages are used to convert the actual temperature history of the concrete to factors that are indicative of how much strength has developed. If the effects of the curing temperature are not to vary with different ages, the equivalent age for a selective curing has to be the same value regardless of temperature history. Under isothermal conditions, Carino(15) showed that the development of strength can be described by a hyperbolic expression (Eq. 1):

$$S = \frac{S_u k_T t}{1 + k_T t} \tag{1}$$

where S = strength at age t, k_T = initial slope of the relative strength (S/S_u) verse t curve at temperature T, and S_u = ultimate strength. Equation 1 can be converted to an equivalent age at a reference temperature (Eqs. 2 and 3):

$$S = \frac{S_u k_r t_e}{1 + k_r t_e} \tag{2}$$

$$t_e = \Sigma \frac{k_T}{k_r} \Delta t \tag{3}$$

where k_r = rate constant at reference temperature of 20°C, and t_e = equivalent age.

The equivalent age is a maturity index, which represents the age at the reference curing temperature. It would result in the same fraction of the limit strength as would result from curing at other temperatures. Saul(1) proposed it by using the datum temperature, and Friesleben and Perdersen (2) proposed it by using the Arrhenius equation. The expressions of equivalent age (t_{es}, t_{ea}) using the Saul model and the Arrhenius's equation are shown in Eqs. 4 and 5, respectively:

$$t_{es} = \Sigma\gamma_s \Delta t = \frac{\Sigma(T - T_o)}{T_r - T_o} \tag{4}$$

$$t_{ea} = \Sigma\gamma_a \Delta t = \Sigma \exp\left[\frac{E}{R}\left(\frac{1}{T_r + 273} - \frac{1}{T + 273}\right)\right]\Delta t \tag{5}$$

where T_o = datum temperature, E = activation energy (kJ/mol), R = universal gas constant (8.3144 J/mol·K), and γ_s,γ_a = affinity ratio of the Saul model and the Arrhenius model, respectively.

Experimental results from this study can be converted into equivalent ages using the Saul model (Eq. 4) and the Arrhenius equation (Eq. 5) when a conventional maturity concept is applied. Equivalent ages by the Saul model can be obtained directly from Eq. 4 by the letting reference temperature (T_r) be 20°C and the datum temperature (T_o) be −10°C. However, equivalent ages by the Arrhenius equation require activation energy. The rate constants are

TABLE 3
Regression results of isothermal curing specimen using Eq. 1.

	W/C = 0.55		W/C = 0.35	
Curing temperature	k_T (1/day)	S_u (MPa)	k_T (1/day)	S_u (MPa)
5°C	0.0597	48.24	0.0897	60.34
20°C	0.2252	40.71	0.3821	54.45
40°C	0.8285	38.06	1.7693	44.80

found from Eq. 1 at curing temperatures, 5°C, 20°C, and 40°C, and then the equivalent age at each temperature is obtained by Eq. 3. Finally, the activation energy is given by the substitution of equivalent ages into Eq. 5 and a regression analysis. Activation energies in this study were 50.31 and 57.29 kJ/mol for w/c ratios of 0.55 and 0.35, respectively. It would be useful to verify the maturity by some direct information on the degree of hydration, chemically bound water, or analysis of the remaining unhydrated cement. This is suggestion for further work, not a requirement for this paper. The values obtained for activation energy compare reasonably well with those obtained by Kjellsen and Detwiler (16). Table 3 shows rate constants, k_T, and limit strengths, S_u, which are obtained by regression analysis of strength measurements of the isothermally cured concrete.

If the effects of curing temperatures on concrete strength are the same with different ages, rate constants and limit strengths with a given temperature–age history, which are expressed by equivalent ages of the Saul model or the Arrhenius equation, must be equal to those at the standard temperature. Experimental results were converted into equivalent ages (t_{es},t_{ea}) of the Saul model and the Arrhenius model, respectively, and regression analysis was conducted on them using Eq. 2. Figures 6 and 7 show the relative rate constants and limit strengths attained from the regression analysis compared to those of the isothermal curing at 20°C with the varying curing points. It is seen from the figures that there is much difference in rate constants

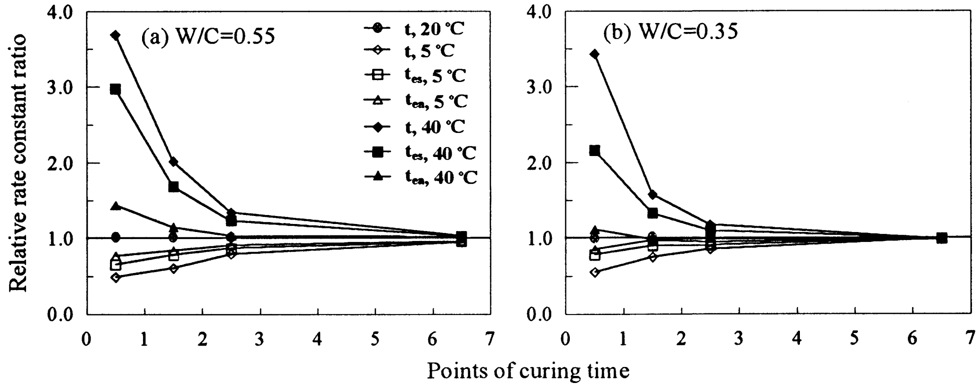

FIG. 6.
(*a*, *b*) Relative rate constant of selectively cured concrete to isothermal curing at 20°C.

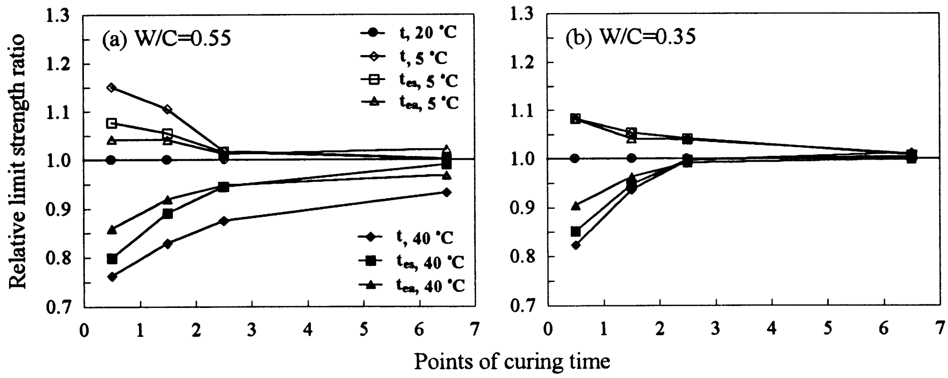

FIG. 7.
(*a*, *b*) Relative limit strength of selectively cured concrete to isothermal curing at 20°C.

and limit strengths at the initial curing point compared with those of the standard temperature curing, and little difference after 7 days. For the selective curing at 40°C with the same equivalent age, figures indicate that the earlier curing point yields higher rate constants but relatively lower limit strengths. This means that the concrete strength with the same maturity can vary with curing points. In the meanwhile, the concrete cured at 5°C gives a lower rate constant at an early stage but higher limit strength than the standard temperature-aged concrete.

As Kjellsen and Detwiler (8), Verbeck and Helmuth (13), and Carino (17) had pointed out these phenomena, a rise in the early curing temperature makes hydration rate and concrete strength increase rapidly. But due to the nonhomogeneous diffusion of hydration product and the difference in thermal expansion coefficients of concrete constituents, the porosity inside cement paste increases and microcracks develop, which finally lead to lowering the strength at the later time.

Therefore, the strength prediction by the maturity method hardly reflects the exact influence of curing points on concrete strength. Especially as the microstructure of cement hydrate as well as the degree of hydration affect the strength development of concrete, it should be noted that different curing points have different effects on concrete strength even at the same curing temperature.

Accordingly, we know that the maturity by the Saul model or the Arrhenius equation could not take into account the effects of initial curing points and the rate that constant model of Eq.2 does not reflect the effects on limit strength caused by the microstructure change of cement paste. As shown in Figures 6 and 7, present experimental results show that rate constants and limit strengths are increasing or decreasing with the curing points, converging to those of the standard temperature curing. Guo (9) suggested that the curing temperature effect on strength increase would diminish slowly with age, and Kjellsen and Detwiler (8) showed the activation energy decreased as hydration proceeded.

Development of the Modified Rate Constant Model

To consider the effects of curing temperature with varying time curing points, Eq. 2 can be modified as shown in Eq. 6:

TABLE 4
Regression results of constants using proposed model.

W/C	Selective curing temperature	Modified Saul model		Modified Arrhenius model	
		A	b	A	b
0.55	Lowered temperature	0.5653	1.1109	0.6855	1.0655
	Elevated temperature	6.0256	0.7482	1.6178	0.8136
0.35	Lowered temperature	0.7258	1.1204	0.8327	1.1142
	Elevated temperature	3.0653	0.8311	1.1146	0.8830

$$S = \frac{S_{ur}(1 - \lambda)k_r t_{em}}{1 + k_r t_{em}} \tag{6}$$

where λ = a strength variation coefficient that is affected by both curing temperature and curing time point, S_{ur} = limit strength at standard temperature, and t_{em} = modified equivalent age.

The equivalent age of Eqs. 4 and 5 in Figure 6 can be expressed as shown in Eqs. 7 and 8 by considering the effects of curing points:

$$t_{em} = \Sigma \gamma_{em} \Delta t = \Sigma \gamma \frac{1 + t_c^2}{a + t_c^2} \Delta t \tag{7}$$

$$\gamma_{em} = \gamma \frac{1 + t_c^2}{a + t_c^2} \tag{8}$$

where γ = equivalent age ratio, t_c = curing period of Δt, and a = constant.

The limit strength of Figure 7 can be expressed by Eqs. 9 and 10:

$$S_u = S_u(T,t) = S_r(1 - \gamma) \tag{9}$$

$$\lambda = \Sigma \frac{1 + t_c^2}{b + t_c^2} \Delta t \tag{10}$$

where b = constant.

Table 4 shows the constant values a and b obtained by regression analysis using Eqs. 8 and 10. Then, the constants a, b are 1.0 on the condition of isothermally cured concrete at 20°C.

Figures 8a and 8b give a comparison of strengths predicted by Eq. 2 with those of a standard temperature curing. In the figure, the equivalent age by the Arrhenius equation reflects the effects of curing temperatures relatively better than that by the Saul model, but there is a large deviation in the early ages.

Figure 8c shows the relative strength predicted by the proposed equation Eq. 6 compared to the standard temperature-cured strength. Figure 8d shows the equivalent age and the limit strength obtained by the modified the Arrhenius equation. Figures 8c and 8d show that the reliability of prediction at the initial stage has much improved. From Figure 8d, we can see that the modified the Arrhenius equation gives higher accuracy than the existing models.

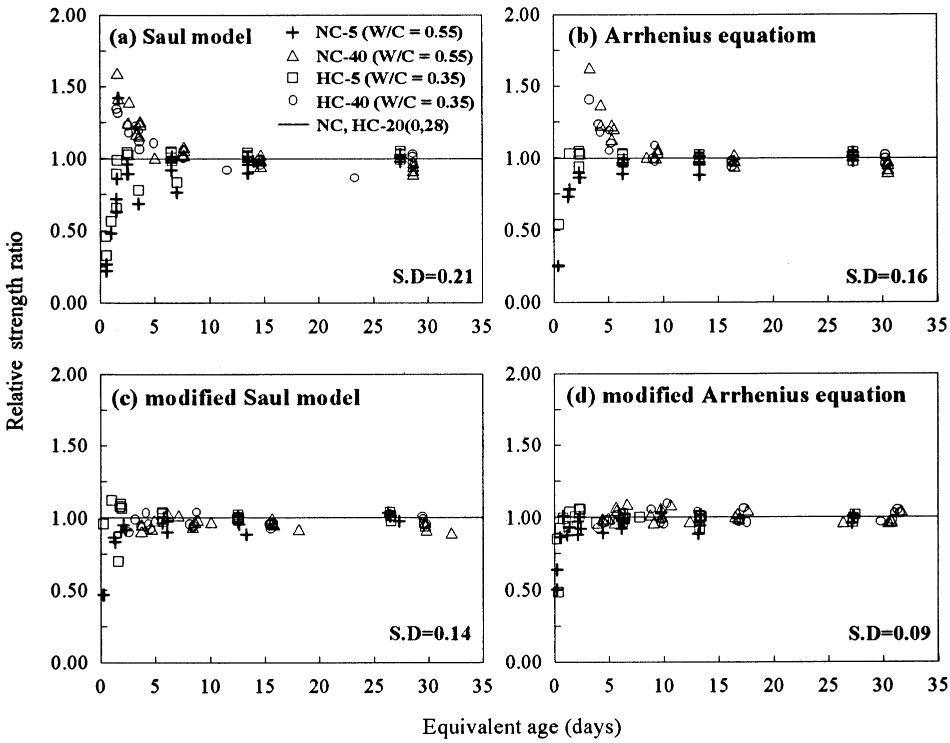

FIG. 8.
(*a*–*d*) Comparison of experimental data and predicted value by existing models and proposed models.

The prediction of concrete strength by means of the maturity concept must yield the same strength for the same mixing ratio and the same equivalent age. However, the conventional maturity concept excludes the time dependency of curing temperatures. Therefore, an ideal maturity function should be one of the functions considers the curing temperature and the curing time points simultaneously. Experimental results and the model equation presented here show this tendency well.

Conclusions

The present study is aimed at conducting experiments to determine how curing temperature affects concrete strength, which varies at different ages, and establishing a model equation to reasonably predict concrete strength based on the experimental results.

The development of strength for various curing histories was investigated with particular regard to the influences of curing time at different ages. The experimental results show that concrete specimens subjected to a high early temperature (40°C) attain a greater early-age strength but eventually attain a lower later-age strength. On the other hand, the specimen subjected to a low early temperature (5°C) has a lower early-age strength but almost the same later-age strength as that of the specimen subjected to the isothermal curing (20°C). From the limited experiments, the change of curing temperatures appears to be effective within 3 days after casting on the later-age strength. The varying temperatures occurring at ages later than 3 days did not seem to have any significant effects on strength.

The proposed model equation, which takes into account effects of curing points for equivalent ages using the Saul model and the Arrhenius equation and introduces the strength variation coefficient into the rate constants and limit strengths, improves the predictability of concrete strength. As a result, it is concluded that the concrete strength with the same equivalent age varies with curing points. Thus, the conventional method for predicting concrete strength by its maturity can hardly reflect the exact time effects of the curing temperature. The effects of the curing points on the curing temperatures should be considered, especially during the initial stage.

Acknowledgments

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