C급플라이애쉬를 사용한 모르터의 응결 및 성숙도

Setting Times and Maturity Functions for Cement Mortars Made with Various Amount of Fly Ash

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요 약

항온의 상태에서 양생된 모르터 시편에 대해 양생온도가 강도발현에 미치는 영향을 알아보기 위하여 rate constant 모델에 대해 살펴보았다. 먼저, C급 플라이애쉬를 사용한 모르터시편의 응결시간을 ASTM 실험방법을 사용하여 구하였다. 그결과 플라이애쉬 대체율이 높아지거나 양생온도가 낮아질수록 응결시간이 지연됨을 알 수 있었다. 본연구에서는 Arrhenius공식을 사용하여 rate constant와 양생온도간의 관계를 표현할 수 있었다. 실험에서 보여주듯이 플라이애쉬량이 증가하면서 활성화에너지가 감소하는 경향을 보여주었다. 또한 활성화에너지는 지수함수로 표현되어지는공식의 'B' 값으로 표현되어지는데 양생온도에 비례한다.

모르터시편의 상대강도와 그에따른 등가재령의 관계를 정립할 경우 rate constant와 affinity ratio가 중요함을 설명하였다. 실험결과 상대강도-등가재령 모델이 실험데이터와 잘 일치함을 보여준다.

Abstract

The rate constant model was reviewed to consider temperature sensitivity of concrete for

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• 본 논문에 대한 토의를 1997년 8월 30일까지 학회로 보내주시면 1997년 10월호에 토의회답을 게재하겠습니다.

estimating strength gain of mortar specimens under isothermal curing conditions. To determine the strength-maturity relations, mortar specimens were made with 10, 20, 30 percent replacement of Type C fly ash and cured at 10, 23, 50 ℃. First, the setting characteristics for mortar specimens made with various amount of Type C fly ash were determined by ASTM penetration resistance test. Slow setting was observed when the amount of fly ash was added more up to 30 percent and curing temperature was lowered. Next, the Arrhenius function was used to represent a relationship between the rate constant and the curing temperature. Resulting data show that the activating energy seems to decrease yet with certain variability as the amount of fly ash increases. It is also explained that the activating energy in the Arrhenius form can be converted into its corresponding B-value in the exponential form but depending on temperature.

Finally, to establish a relationship of relative strength gain of mortar specimens and equivalent age, importance of its parameters such as the rate constant at a reference temperature and the affinity ratio is discussed. Test results show that there is good agreement between the experimental data points and the relative strength-equivalent age model in all the test series.

Keywords : maturity function, equivalent age, sething times, relative strength

1. Introduction

Strength of a given concrete mix depends on its age and temperature history if concrete is properly placed, consolidated, and cured with sufficient water. Strength-dependence on the temperature history of the concrete associated with time can be accounted by the maturity concept. The maturity is used for the following purposes: (1) to predict concrete strength, (2) to decide the form stripping time, (3) to find temperature protection period, (4) to accelerate the construction schedule, and, (5) to reduce costs.(1)

It has been observed that the Nurse-Saul function does not provide accurate expression to represent the strength development of concrete in some conditions. Thus, alternative time-temperature functions were presented by Freiesleben Hansen and Pedersen(2) based on the Arrhenius equation and an exponential function by Carino.(1,3,5) These two maturity functions have been found to be more accurate than the Nurse-Saul function.

In this study, the Arrhenius function was used to represent the maturity function. The activating energy which is a parameter in the Arrhenius equation must be basically determined from a heat of hydration test. However, similar values of activating energy were reported from both heat of hydration test and mechanical strength of mortar test.(1) In addition, almost the same activating energy was obtained from test results between mortar specimens and concrete specimens. Thus, tests of mortar specimens appear to provide information necessary to incorporate the Arrhenius equation.[1]

In the hyperbolic strength-age relationship, this paper examines the use of initial offset time with a value between the initial setting and the final setting times determined from the penetration resistance test. From these findings, the setting characteristics for mortar specimens made with various amount of Type C fly ash were studied as supplement to the maturity function. Finally, a relative strength model based on the hyperbolic function is reviewed with respect to the setting time and the affinity ratio.

2. Objective and scope

The objective of this study was to investigate the proposed rate constant model[11,12] and to improve the proposed rate constant model. This study had the following procedures:

(1) To examine the characteristics of initial and final setting times of mortars using the penetration resistance test[6] and, consequently, whether a parameter of the initial offset time in the hyperbolic model could be obtained from this test

(2) To determine a relationship between the rate constant and curing temperatures and express the equivalent age as a function of the activating energy

(3) To express the relative strength-equivalent age using a similar form as the hyperbolic strength-age model

For the study, the following variables were used.

(1) Curing temperature (10, 23, 50 ℃)

(2) Water-cement ratio (about 0.42)

(3) F/A addition (0, 10, 20, 30 %)

3. Maturity function

3.1 Initial factor t_0

The initial age, t_0 is affected by curing temperatures and specimen sizes, w/c ratios, and admixtures. First, an increase of curing temperature leads to a rapid setting, thus a decrease of t_0, and vise versa. And specimen sizes affect t_0, too.

Next, there is a linear relationship between t_0 and w/c ratio.[2] As the water cement ratio increases, t_0 in mortar mixtures increases. However, Carino reported that t_0 was independent of the w/c ratio.[3] He concluded that the w/c ratios of concrete mixes do not have significant effect on relations between t_0 and temperature. But nothing is more dominant for the inital age than the characteristics of cements or admixtures. The setting characteristics of concrete were summarized for various cement types and admixtures as well as w/c ratios.[7] It was noted that an increase of cement content but holding the same w/c ratio also reduces setting time.[8,9]

There have been a few attempts to find the link between cement setting and concrete strength gain. Carino[4] showed that the final setting time was the beginning of the development for strength gain at normal temperature. It was reported[9] that the offset maturity (initial t_0) was very close in a value to the measured maturity at the final setting time determined by the penetration resistance, though some of the values were shown to be between initial and final setting times. From this observation, t_0 in the study was assumed to be ranged between the initial setting time and the final setting time.

3.2 Strength gain function

Strength gain of concrete was described by a hyperbolic curve under an isothermal curing condition. The three-parameter hyperbolic function for the strength gain of concrete was proposed by Carino which was originally presented by Bernhardt.(1,6) The rate of strength gain is assumed to be strength function, f(S), and temperature history function, k(T):

$$\frac{dS}{dt} = f(S) \cdot k(T) \qquad (1)$$

Based on empirical expression of degree of relative strength relationship,

$$f(S) = S_u \cdot \left[1 - \frac{S}{S_u}\right]^2 \qquad (2)$$

and if S_u is independent of curing temperature, then the following integrated form is obtained:

$$\int_o^S \frac{dS}{\left[1 - S / S_u\right]^2} = S_u \int_{to}^{t} k(T)dt \qquad (3)$$

Carino expressed Eq.(3) using 't_o' that strength equals zero not at zero age but at a later age.(3) In other words, strength development does not begin until setting has occurred. Based on the observation of the offset time of cement chemistry, Carino introduced an offset maturity or initial time 't_o'. For the isothermal conditions, the general strength-age relationship reduces to a following equation:

$$S = S_u \frac{k_T (t - t_o)}{1 + k_T (t - t_o)} \qquad (4)$$

The above strength function has three unknown parameters: (1) t_o, the initial age when concrete strength begins to develop, (2) k_T, the rate constant, which is temperature-related function and the initial slope of the curve, and (3) the limiting strength S_u. The proper use of its equation depends on the correct choice of t_o as well as k_T or S_u.

In Eq. (4), the temperature history of concrete at early ages affects its limiting strength, S_u. As the temperature is increased at early ages, the limiting strength is reduced.

In the above strength development function, k_T is affected by several factors: curing temperatures, w/c ratios, admixtures. First, k_T is obviously increased as curing temperature is increased. It usually takes less time for the accelerated cured specimens to achieve 50 percent of the ultimate strength since k_T is the reciprocal of the time after t_o to reach 50 percent of the ultimate strength. Next, significance of the rate constant k_T is dependent on w/c ratios. Carino's later work shows that for some of mixtures, the parametric value E or B which will be shown in Eqs. (7) and (9) was scattered in the correlration between high w/c ratio and low w/c ratio.(7) Similarly, admixtures such as fly ash or silica fume and accelerator or retarder have an influence on k_T.

Carino(2,3,4,5) treated regression analysis for determining the unknown parameters in a proposed strength-age form, based on the lowest standard error for the estimate of k_T. There are two steps in Carino's approach. First step is to get the limiting strength S_u from the reciprocal value of the intercept of the following formula:

$$\frac{1}{S} = \frac{1}{S_u} + \frac{1}{k_T S_u} \cdot \frac{1}{(t - t_o)} \qquad (5)$$

Having obtained the estimated value of Su, next step is to obtain values of k_T and to estimated from the linearized form as follows:

$$\frac{S}{S_u - S} = -k_T \cdot t_o + k_T \cdot t \qquad (6)$$

3.3 Rate constant-temperature relationship and equivalent age

A large number of different rate constant-temperature relationsips has been proposed. Carino compiled most of these proposed functions. As well-known, there are three proposed rate constant and temperature relationships:(1) the linear function, (2) the Arrhenius function, and (3) the exponential function.

First, the linear function is represented using the datum temperature. The datum temperature is temperature at which the rate constant is zero. It has been used in the traditional Nurse-Saul maturity function.

Second, the Arrhenius function was introduced by Freiesleben Hansen.[12] Since then, the Arrhenius function has been widely used in Europe. This Arrhenius function was based on a production rate of atomic arrangement in a solid state. An experimental work on the rate of atomic reactions has shown that the rate of movement is related to temperatures by the Arrhenius equation as follows:

$$k(T) = Ae^{-Q/T} \qquad (7)$$

where A = a constant, day^{-1}
Q = E/R, K
E = activating energy, J/mol
R = universal gas constant, 8.3144 J/(mol · K)
T = absolute curing temperature, K

By taking natural logarithm of Eq. (7), the ratio of activating energy to the gas constant simply represents the slope of the following formula:

$$ln[k(T)] = ln[A] - \frac{E}{R} \cdot \frac{1}{T} \qquad (8)$$

Third, the exponential function was proposed by Carino.

$$k(T) = Ae^{(BT)} \qquad (9)$$

where B = temperature sensitivity factor, 1/℃
T = curing temperature, ℃

Carino showed that both Arrhenius and exponential functions represent more accurately the effect of temperature on strength development. He also noted that the Arrhenius and the exponential functions are shown to be similar. Activation energy in the Arrhenius equation could be converted to the value of B in the exponential function. For thess relations, Carino reported there is strong correlration between E and B values as B=0.00135E where E was expressed as KJ/mol. However, it is obvious that if one equates Eq. (7) and Eq. (9) at the reference temperature in 23℃, B would be expressed as follows:

$$B = \frac{E}{R} \frac{1}{296 \cdot (273 + T)} \qquad (10)$$

The value B is dependent on curing temperature as well as activating energy. In curing temperature range from 10 to 50

℃, the parameter B is ranged from 0.001258E to 0.001436E. But, B is 0.00137E in a reference temperature of 23℃.

An equivalent age or equivalent time represents a certain curing period at a reference temperature that would result in the same equivalent age that would occur at different curing temperature conditions. Its concept was introduced first by Rastrup.(11) In the Arrhenius function,

$$\gamma = \frac{k_T}{k_r} = e^{-\frac{E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \tag{11}$$

in which γ is the affinity ratio, and T_r as an absolute reference temperature. The equivalent age is calculated from the experienced history of temperature in the concrete structures or specimens. For the isothermal curing condition case, it was determined by the following formula:

$$t_e = \int_o^t \left(\frac{k_T}{k_r}\right) \cdot dt = \frac{k_T}{k_r} \cdot t \tag{12}$$

Finally, $k_T t = k_r t_e$ could be obtained in a constant curing condition from the above expression.

3.4 Relative strength development

It has been assumed in the strength-age model that the limiting strength of concrete specimen is not affected by the maturity (or equivalent age). However, S_u decreases as the curing temperature increases. Thus, expression (4) does not provide unique strength versus equivalent age relationship. Furthermore, the curing temperature affects the initial offset time as well as the ultimate strength. From these features, relative strength development which is based on the fractions of ultimate strength in terms of equivalent age was proposed by Carino as follows:

$$\frac{S}{S_u} = \frac{k_r(t_e - t_{or})}{1 + k_r(t_e - t_{or})} \tag{13}$$

where t_{or} = the best fit value of the offset equivalent age.

Based on Eq. (12), Eq. (13) could be rearranged as:

$$\frac{S}{S_u} = \frac{k_r(t_e - \gamma t_o)}{1 + k_r(t_e - \gamma t_o)} \tag{14}$$

Comparing Eqs. (13) and (14), difference is t_{or} and t_o only. The offset equivalent age of t_{or} was determined from trial and error to represent the best fit value of the proposed curve.(2) For simplicity, t_{or} can be γt_o at the room temperature if the reference temperature is assumed to be the room temperature.

4. Experimental procedures

4.1 Fly ash

Fly ash has been widely used in concrete structures as a partial replacement of cement for many years. Attempts have been made to use fly ash usually by 30 percent(8) and even raise to 58 percent(8) replacement of cement by weight. The reduction of temperature rise by the replacement of fly ash in a mass concrete structure has a promise in using fly ash to reduce possible thermal cracking at an early age.(8,9) As advantages of using fly ash, durability and strength in hardened concrete as well as reduction in temperature rise in fresh concrete were found.

According to Barrow's work(7), as curing temperature is raised, the relative strength

Table 1 Chemical and physical composition for fly ash

Requirements	Percentage
SiO_2	33.45
Al_2O_3	18.61
CaO	28.04
Fe_2O_3	6.87
MgO	5.12
SO_3	2.32
Moisture content	15
Loss on ignition	0.23
Finess	15.3

increases in 24 hours showed to be greater for mortar containing type C fly ash than that for mortar without fly ash. It appears that the strength of concretes made with fly ash is more dependent on the curing temperature than concrete mixtures without fly ash.(8)

Two studies reported the retarded setting time for the use of fly ash in concrete.(9,12) Initial setting times of various concrete mixtures which have but 58 percent replacement of cement by mass ranged from 4.5 hours to 13.2 hours.(2)

Table 1 lists chemical and physical composition for type C fly ash which was used in this study.

4.2 Mix design and curing

A total of four different concrete mixes were made. Type I cement from the same sources was used for all mixes. The proportions of cement-fly ash mixtures used are given in Table 2. The coarse aggregate was crushed lime stone with 38.1 mm maximum size and natural sand was used as fine aggregate. As an admixture, type C fly ash was used for 10, 20, and 30 percent replacement of cement. The water-cement ratios for all mixes are almost identical. It varied between 0.42 to 0.45. The mix proportions of percentages by weight are shown in Table 3.

Table 2 Proportions of cementitious materials for cement-fly ash mixtures

Test series	Symbol	Proportions by percentage	
		Cement	Fly ash
Cement	Control	100	0
Cement + 10% Fly ash	F/A 10%	90	10
Cement + 20% Fly ash	F/A 20%	80	20
Cement + 30% Fly ash	F/A 30%	70	30

Table 3 Concrete mixture proportions per m^3

Test series	Cement kg	F/A kg	Gravel kg	Sand kg	W/C ratio
Control	391	0	1155	621	0.44
F/A 10%	352	39	1155	621	0.42
F/A 20%	313	78	1155	621	0.42
F/A 30%	274	117	1155	621	0.42

For specimen preparation, ASTM C 403 method was adopted.(6) After mixing the materials, materials larger than No. 4 (4.75-mm) sieve were sieved out. Mortars from the concrete mix by sieving it through a No. 4 was remixed by hands.

First, a 152×152 mm cylindrical mortar specimen was made using cardboard mold. Next, cubic mortar specimens were prepared using brass mold which has three 51mm cube compartments. After molding, the specimens in the mold were consolidated using a vibrating table. And the mortar specimens were moved into water baths which were controlled in the environmental chambers: approximately 9, 23, and 48℃.

Temperature of a cubic specimen was monitored through an embedded thermocouple, which was connected to the datalogger. It was found that the mortar specimen reaches the equilibrium temperature within about one hour after the first addition of water. The specimens cured at about 9, 23, 48℃ will be referred to as cold-, room-, and hot-cured specimens, respectively.

4.3 Setting and strength tests

The 152×152mm cylindrical mortar specimen was used to monitor the penetration resistance for each mix at each temperature curing condition. According to ASTM C 403 test procedure,[15] the times required for the mortar specimen to reach 3.5 MPa (500 psi) and 27.6 MPa (4000 psi) were used to define the initial setting and the final setting times, respectively.

Compressive strength tests were performed on the mortar cubes by using a universal hydraulic testing machine of 120 MPa capacity. The cubes were loaded in accordance with ASTM C 109 standard procedure.[13] For each treatment, three cubes were tested at six to seven different ages. The remainder of the mortar cubes were demolded at the time of first strength test. At each age, the average value of three compressive strengths was used in the analysis.

4.4 Test results

Table 4 summarizes the initial and the final setting times for all the mix designs which were determined by the penetration resistance tests. Fast setting was observed in all the mixes as temperature increases for all the mixes. In Table 4, the initial setting times at the curing temperature of 9 ℃ and 48℃ were 0.333 day (8.0 hours) and 0.129 day (3.1 hours) for the mortar mix made with Type I cement plus 20 percent fly ash (F/A 20%), respectively. Figure 1 shows the penetration resistance curves of the mortar specimen contained 20 percent fly ash at three different curing temperatures (9, 23, and 48 ℃).

Table 4 Times of initial and final setting for test series

Test series	Setting times					
	Cold (8-9 ℃)		Room (20-25 ℃)		Hot (46-50 ℃)	
	t_i^a day	t_f^b day	t_i day	t_f day	t_i day	t_f day
Control	.217	.312	.146	.192	.104	.125
F/A 10%	.250	.421	.146	.196	.125	.146
F/A 20%	.333	.479	.188	.250	.129	.154
F/A 30%	.458	.646	.208	.264	.150	.179

a: initial setting time
b: final setting time

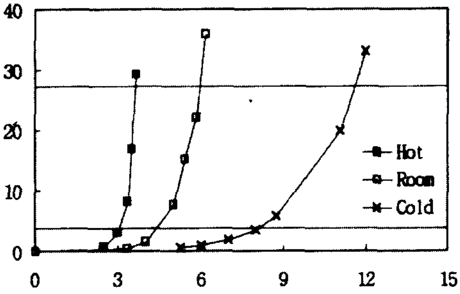

Fig. 1 Results of penetration resistance for F/A 20% mortar mixes

The penetration resistance curves for all the mix designs at about 9 ℃ were shown in Fig. 2. As expected, an addition of Type C fly ash tends to slow the hardening of the mixtures.

Determined by the penetration resistance test, the initial and final setting times of the mixes were utilized for upper and lower limits for the initial offset time in a regression analysis (Eq. (4)).

Then, the best-fit values of parameters

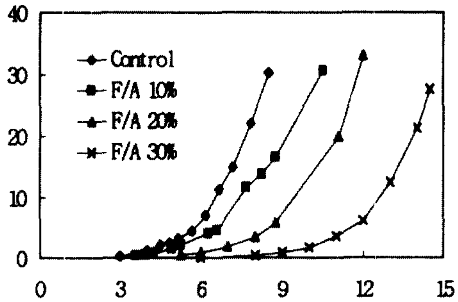

Fig. 2 Results of penetration resistance for all the mortarmixes at 9℃

(S_u, t_o, and k_T) in Eq. (4) were obtained from the least square analysis with average compressive strength data at test ages. Their results are given in Table 5. As discussed before, acceleration of the curing temperature leads to a decrease of the ultimate strength. It turns out to be true in all the test series. Table 5 also shows values of t_o obtained from the least square analysis. With an exception of t_o from F/A 10% series at room temperature, values of t_o were increased as the amount of fly ash increases. In Table 5, the rate constant results, k_T are also tabulated. As the curing temperature increases, values of k_T tended to increase greatly.

Table 5 Strength development parameters for test series

Test series	Curing temperature ℃	Su MPa	kT 1/day	to day
Control	8.8	89.4	.186	.342
	20.0	73.9	.482	.146
	46.9	55.9	1.415	.104
F/A 10%	8.8	82.6	.285	.421
	24.7	68.4	.746	.196
	45.8	58.8	2.226	.125
F/A 20%	8.8	75.5	.271	.479
	21.6	65.0	.615	.188
	49.9	61.4	1.329	.129
F/A 30%	8.9	75.7	.199	.646
	24.8	74.3	.414	.251
	50.0	59.2	1.201	.150

To establish a relationship of the rate constant in terms of its curing temperature, Eq. (8) was used. Figure 3 shows the relations of rate constants and reciprocal values of absolute temperatures. Using Eq. (8), the best-fit value of activating energy which is the slope of Fig. 3 was calculated. Then the range of the value 'B' for the exponential function in Eq. (9) was calculated by using the conversion expression in Eq. (10).

Table 6 lists some values of activating energy for ordinary Type I portland cement reported by other researchers as well as test values in this study. From Table 6, activating energy of the control mix was 38.5 KJ/mol while F/A 10%, F/A 20%, and F/A 30% mixes produce 41.5, 28.2, and 33.2 KJ/mol, respectively. Test results reveal that the activating energy seems to decrease but there was certain degree of variability as the amount of fly ash increases. The test results seem to be reasonable, comparing with some reported data in Table 6. Except for the chemical shrinkage test and 61 to 62 KJ/mol[illegible] of activating energy from compressive strength, a range of 41 to 46 KJ/mol of activating energy was reported for Type I portland cement determined by other researchers and their different tests methods such as the heat of hydration, the x ray diffraction, chemical shrinkage, or compressive strength. However, presently there is not many published data on the effect of activating energy of mortars contained different replacement of cement by fly ash. Tank[14] reported 30-32 KJ/mol of activating energy for mortar or concrete specimens made with Type I cement which

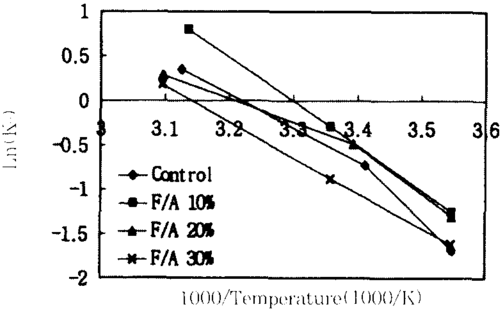

Fig. 3 Relations of natural logarithm of rate constant and reciprocal value of absolute temperature

Table 6 Activation energy (E) for mortars for the test series and some referenced values

Test Series	Value E KJ/mol	Value B 1/℃	Reference	
			Ref[ ][a].	W/C ratio
Control	38.524	.049-.055	46[2][b]	-
			50-80[2][c]	.40-.76
			44[2][d]	.40
			41-44[2][e]	.55
			61-62[8][e]	.45
F/A 10%	41.461	.052-.060		
F/A 20%	28.196	.036-.041	30-32[8][e]	.45
F/A 30%	33.150	.042-.048	-	

a : reference number
b : determined from heat of hydration
c : determined from chemical shrinkage
d : determined from x ray diffraction
e : determined from compressive strength

contain 20 percent replacement of fly ash[11] while test reults in this study was 28.2 KJ/mol.

Finally, a relative strength gain was investigated in terms of an equivalent age by using Eq. (14). Meanwhile, affinity ratio based on 23℃ as a reference temperature was calculated by using Eq. (11) and shown in Table 7 and Fig. 4. Fig. 4 shows that an increase of activating energy (from the control mix to F/A 30% mix) leads to more nonlinear curve. The products of affinity ratio and initial offset time are listed at different curing temperature in Table 7. Unfortunately, values γt_o, wer not very close in different curing temperatures. But the value of t_o at room temperature was used for the relative strength model. One may find that the value of to does not affect Eq. (14) greatly as the equivalent age goes up. Strength value at a certain equivalent age was divided by the corresponding ultimate strength Su and the relative strengths were plotted in terms of their equivalent age. For the isothermal curing condition, the equivalent age is the products of the actual age and the affinity ratio. Finally Figs. 5 and 6 show that there is good agreement between the relative strength model and the relative strength-equivalent age data.

6. Summary and conclusions

The rate constant model was reviewed to account for temperature sensitivity to strength development of mortars which contain various amount of Type C fly ash. In this study, the Arrhenius function was adopted to relate rate constants to curing

Table 7 Affinity ratio and offset time for the test series

Test series	Curing temperature ℃	γ	t_o day	$\gamma x t_o$ day
Control	8.8	.454	.342	.155
	20.0	.852	.146	.124
	46.9	3.220	.104	.335
F/A 10%	8.8	.428	.421	.180
	24.7	1.101	.196	.216
	45.8	3.336	.125	.417
F/A 20%	8.8	.561	.479	.269
	21.6	.947	.188	.178
	49.9	2.597	.129	.335
F/A 30%	8.9	.510	.646	.329
	24.8	1.085	.251	.273
	50.0	3.083	.150	.463

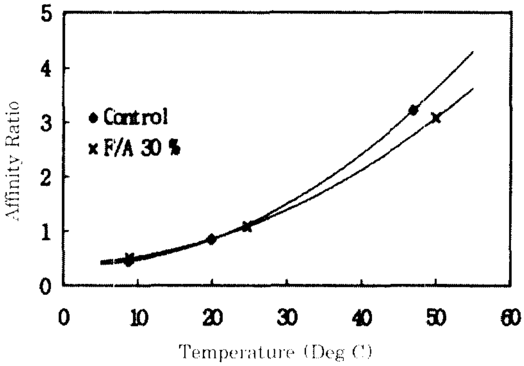

Fig. 4 Affinity ratio with temperature based on Arrhenius equation at 23℃

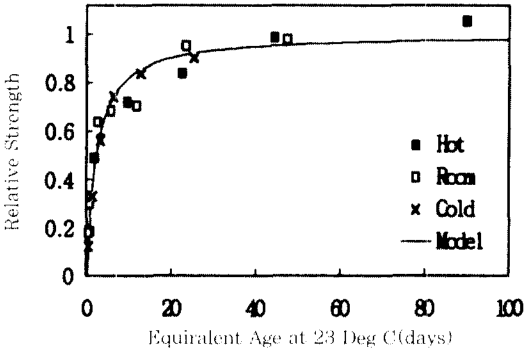

Fig. 5 Relative strength vs. equivalent age using Eq. (14) for control mix

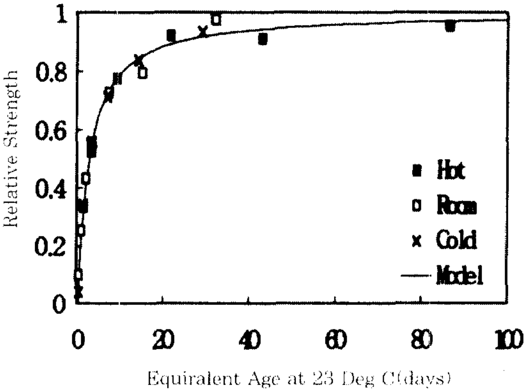

Fig. 6 Relative strength vs. equivalent age using Eq. (14) with F/A 30% mix

temperatures. The setting characteristics for the test series were studied to use their information as the initial offset time in the relations of strength-age development of concrete. Then, the relative strength gain of concrete was represented as a function of the equivalent age. Based on this study, the following conclusions can be drawn from the test results:

(1) The addition of Type C fly ash mixed with one-to-one basis by weight slowed down the hydration of the mixtures up to 30 percent of replacement for cement.

(2) The times of initial and final setting were shortened as the curing temperature was raised for all the test series.

(3) The number of unknown parameters on the hyperbolic strength-age relations in Eq. (4) could be reduced by two if assumed that to would be determined at a time between the initial setting and the final setting. The lower and upper limits of to was obtained from the penetration resistance test of ASTM.

(4) It was shown that activating energy of the mortars appeared to decrease as the replacement of cement by fly ash increased but there was certain variability.

(5) The value of activating energy is converted to corresponding B-value in the exponential function but dependent on temperature.

(6) The relative strength gain of mortar can be estimated from the relations of relative strength and equivalent age in Eq. (14). It shows good agreement between the experimental data points and the model curve for all temperature conditions in all the test series.

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