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Use of maturity methods to estimate the setting time of concrete containing super retarding agents

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ABSTRACT

In this study, we examine a method for estimating the setting time of concrete containing super retarding agent (SRA) under various curing temperatures. To estimate the setting time, the equivalent age method using the apparent activation energy (E_a), proposed by Pinto et al., is applied. Increasing the SRA content leads to considerable retardation of the initial and final sets of concrete, whereas increasing the curing temperature shortens the initial and final set times regardless of the SRA content. E_a values at the times of initial and final sets obtained using the Arrhenius function differ for different mixtures. They are estimated to be in the range 30–35 kJ/mol for the control mixture, which is similar to or slightly lower than the results of a previous study, but are in the range 20–40 kJ/mol in concrete containing SRA, which is lower than that for conventional concrete. We apply E_a according to the SRA content to Freisleben-Hansen and Pedersen's equivalent age function and find that the equivalent age is nearly constant regardless of the curing temperature. This implies that the concept of maturity can be applied to the estimation of the setting time of concrete containing SRA. The setting time estimated using the equivalent age according to the SRA content and curing temperature is presented herein. A good agreement is observed between the estimated setting time and measured setting time. Thus, the method for estimating the setting time suggested by Pinto is applicable to the region of concrete containing SRA.

1. Introduction

Super retarding agent (SRA) is a long-term retarding admixture that, depending on its content, delays the setting and hardening of concrete from several hours to several days without having a detrimental effect on strength development. Advantages of SRA include the suppression of cold joints resulting from long transport distance, long-term storage and consecutive execution in placing concrete due to its prolonged workability as a result of setting time delay. SRA also has superiority in reduction of cracks resulting from the heat of hydration in mass concrete works.

Rickert [1] reported the use of SRA as a recycling aid for retarding the hydration of cement residues in the wash water of actual mixer drums so that the wash water can be reused immediately as part of the mixing water. According to Rickert's research, the addition of SRA can suppress the hydration reactions so that even after more than 72 h, concrete can be used as the starting material for the production of concrete after the addition of a new batch mix. In addition, Okawa et al. [2] described the reuse of returned concrete using a stabilizer (similar to a retarder or SRA) for direct control of the hydration of cement for retarding residual concrete.

Several studies have been conducted on SRA. For example, Taplin [3] examined 80 kinds of compounds and classified them into admixtures of strong retardation and those of weak retardation on the basis of a set delay time of 17 h when they were added as 1% of the cement weight. He demonstrated that among the chemical agents, those with a HO–C–C=O group in their molecular structure had a strong retardation effect. Young [4] proposed a theory for the retardation of setting caused by the addition of sugar and indicated that adsorption of sugar onto both hydrating particles and hydration products is closely related to the cause of retardation.

Thomas and Birchall [5,6] showed that retardation of cement is attributed to complexation of sugar onto phases containing calcium and proposed that sugars delay hydration by increasing the solubility of cement and being adsorbed onto calcium hydroxide and C–S–H inhibiting their growth. Juenger and Jennings [7] experimentally reported the effect of temperature on the hydration of a cement paste containing sugar. They indicated that the addition of sugar contaminates hydration products or hydrating cement particles or both and alters the microstructure of C–S–H, thereby changing the formation process and surface area. When the effects of contamination are overcome, ions react to form less dense products in the open pore space, resulting in a higher surface area C–S–H.

The author and coworkers [8–11] conducted a series of researches for improving the quality and workability of concrete by

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adjusting the setting time of concrete with the use of SRA. In those researches, they examined the effects of the type of SRA, its content, and curing time on concrete. Subsequently, an optimal SRA agent combination that achieves the required delay of setting time in the most effective and economical way without any negative effect on the physical properties of the concrete was also presented.

Newly developed SRA is a sucrose-based SRA using sugar. In terms of retarding setting, it showed performance similar to that of existing SRA using gluconic acid and pyruvic acid, but in terms of economic efficiency, it was superior to existing SRA. Adding the developed sucrose-based SRA to concrete placed in the bottom section in a mass concrete work where placing lift was divided reduced the difference between the temperature of hydration heat in the center and the surface section and lowered the peak temperature. As a result, cracks resulting from the heat of hydration were greatly reduced [10].

In the construction field, however, concrete is subject to various temperature conditions such as changes in air temperature and the effect of the heat of hydration, and in such cases, the use of SRA is considered to have a significant effect on the setting and strength development of concrete. That is, when SRA is used, it is important to accurately estimate the setting time and strength development by considering the effect of curing temperature, in order to facilitate quality control and subsequent schedules such as reviewing the record of hydration heat, determining the form removal time, and deciding the term for preventing frost damage at an early age.

Strength development is generally estimated using maturity methods that consider the combined effect of temperature and time. There are two different maturity methods that consider simply the relation between time and temperature and consider the degree of chemical reaction of cement. Many researchers have reported that the application of maturity is possible from the point of time when the strength of concrete begins to develop after the final set. However, strictly speaking, maturity is used to estimate the effect of the temperature on the hydration reaction rate of cement. It is well known that the hydration reaction begins, though only gradually, before the point of setting and that the hydration reaction is the most important factor in setting. Accordingly, it is considered possible to apply maturity with regard to the hydration reaction when estimating the point of setting from the viewpoint of the hydration reaction of cement [12].

Pinto et al. [12] reported that the concept of maturity can be applied to the estimation of the setting time. According to their report, apparent activation energy (E_a) based on the speed of the hydration reaction can be estimated using the setting time; the obtained E_a is in good agreement with the value presented in ASTM C 1074 [13]. When E_a is applied to Freisleben-Hansen and Pedersen's [14] equivalent age function, it is possible to estimate a relatively accurate setting time.

With regard to the estimation of the setting time, Dodson [15] termed the water to cement ratio (W/C) the "omega index factor" and attempted to propose a model for setting time estimation using this factor. In addition, to estimate the setting time of concrete containing fly ash, Brooks [16] proposed a model function considering the Blaine fineness, density, W/C and temperature of cementitious material, and the chemical proportion of blended cement. He reported that the proposed model can estimate the setting time for ordinary Portland cement concrete and fly ash concrete containing 60% fly ash.

However, few studies have been conducted on the estimation of the setting time of concrete using SRA, which is necessary for quality control with respect to the setting behavior of concrete using SRA. Therefore, in this study, we examined the setting time of concrete according to SRA content and curing temperature to provide applicability of maturity method to the estimation of setting time of concrete containing SRA.

2. Theoretical background

2.1. Maturity

Maturity is a function that takes into account the combined effects of time and temperature on the strength development of concrete, which is calculated above a datum temperature. Generally, maturity can be determined from the linear expression proposed by Saul (Eq. (1)) and an equivalent age consideration (Eq. (2)) proposed by Freisleben-Hansen and Pedersen based on the Arrhenius equation (Eq. (3)), which explains the effect of temperature on the rate of the chemical reaction. Presently, because of the mathematical simplicity of the maturity proposed by Saul, the application of Saul's maturity appears to be more attractive than the equivalent age consideration based on the Arrhenius equation [17].

However, Saul's maturity has the shortcoming that temperature has a linear effect on strength development and the linear maturity method proposed by Saul is inherently less accurate for concrete mixtures having high activation energies, which is a key factor in the equivalent age consideration. A higher value of the activation energy implies high-temperature sensitivity of the rate constant, and variation of the rate constant with curing temperature becomes more nonlinear as the activation energy increases.

Accordingly, the equivalent age method is significantly more useful than the traditional maturity method and represents the variation in the rate constant with curing temperature well over a wider temperature range.

(1) Maturity based on a linear relationship between temperature and time

$$M = \int_0^t (T_C - T_0)dt \tag{1}$$

where M: maturity (°C day); T_c: temperature of concrete (°C); T_0: datum temperature (accepted value: −10 °C).

(2) Maturity based on the Arrhenius law

$$K_T = A \cdot \exp\left(-\frac{E_a}{RT}\right) \tag{2}$$

where k_T: rate constant; A: frequency factor; E_a: apparent activation energy (kJ/mol); R: gas constant (8.314 J/mol K); T: temperature (K, 273 + °C).

$$t_e = \int_0^t \exp\left[\frac{E_a}{R} \cdot \left(\frac{1}{T_r} - \frac{1}{T}\right)\right]dt \tag{3}$$

where t_e: equivalent age (days); T_r: absolute temperature at 20 °C (293 K).

2.2. Apparent activation energy

Activation energy is the minimum energy required to activate a chemical reaction. However, because the hydration reaction of cement occurs through simultaneous multiple reactions involving several minerals, it can be termed the apparent activation energy (E_a) rather than the activation energy [17]. E_a required in the hydration reaction of cement can be estimated on the basis of ASTM C 1074.

Portland cement has different patterns of hydration reactions at different stages, such as several hours after mixing, during the setting process, and at a later age; therefore, E_a has different values at different times after water and cement come into contact and that the values are affected by the characteristics of cement and admixtures.

Some researchers reported that E_a ranges from 33.5 to 47 kJ/mol at an early age and from 10 to 20 kJ/mol at a later age [18,19]. In

ASTM C 1074, E_a is reported to be from 40 to 45 kJ/mol for ordinary Portland cement without admixture and is calculated using Eq. (2). First, the set and compressive strengths of mortar cured under three different temperature conditions are measured for each age (after periods of 2, 4, 8, 16, 32 and 64 times the period for the final set). And then, a linear regression equation is obtained through regression analysis of the inverse of the age and the inverse of the strength. The rate constant k_T is obtained by dividing the intercept of the regression line by the slope. In addition, Eq. (4) is obtained by taking the natural logarithm of both sides of Eq. (2) [13].

$$\ln k_T = \ln A - \frac{E_a}{R} \cdot \frac{1}{T} \quad (4)$$

E_a can be obtained from Eq. (4), in which E_a/R is the slope of the linear regression equation obtained by plotting $\ln(k_T)$ and $1/T$ from regression data.

2.3. Application of maturity to estimation of setting time

According to Pinto et al. [12], several procedures and assumptions are necessary to apply maturity to the estimation of the setting time. First, E_a from the initial set to the final set should be obtained under the assumption that microstructure formation occurs to some degree (hydration occurs to some degree) due to the cement hydration reaction even at the initial and final sets. When α_i is the degree of hydration at the initial set and α_f is the degree of hydration at the final set, the following assumptions are made.

(1) Time t_i required for the initial set is equivalent to that required to reach α_i.
(2) Time t_f required for the final set is equivalent to that required to reach α_f.

Because a faster hydration reaction corresponds to shorter initial and final set times, the times required to reach the initial and final sets are inversely proportional to the rate constant of the hydration reaction ($k_T \propto 1/t_i$).

Under the abovementioned conditions and assumptions, E_a values at the initial and final sets can be calculated using the Arrhenius function. According to Pinto's research, $\ln(1/t_i)$ is substituted for $\ln(k_T)$ in the Arrhenius function, and the relationship between $\ln(1/t_i)$ and the inverse of the absolute temperature (T) is determined, and through regression analysis, E_a values at the initial and final sets are calculated. If E_a calculated in this way is applied to Freisleben-Hansen and Pedersen's equivalent age function, equivalent ages at the initial and final sets can be obtained.

3. Experimental plan

3.1. Design of experiment

The experimental plan is shown in Table 1. Mixture proportions of concrete are provided in Table 2. W/C was fixed at 40%. The mixture proportions of conventional concrete were determined to achieve a target slump of 15 ± 1 cm. The dosage of SRA ranged from 0% to 0.6% by cement weight in 0.15% increments. SRA was prepared by mixing white sugar, viscosity modifying agent, and air entraining (AE) agent of given proportions to achieve a bleeding resistance and target air content. Specimens for measuring the setting time were placed in a chamber at 5, 20, 35 and 50 °C until final setting. A total of 20 mixtures were prepared.

3.2. Materials

Cement used in this experiment was ordinary Portland cement produced in Korea. Its physical properties are given in Table 3. River sand was used as fine aggregate, and crushed stone with a maximum size of 20 mm was used as coarse aggregate. The physical properties of each type of aggregate are shown in Table 4.

The SRA was mainly composed of white sugar. However, the individual use of white sugar resulted in bleeding and a loss of air content for concrete. Hence, a polyethylene oxide (PEO)-based viscosity-modifying admixture for restricting segregation and the AE agent

Table 1
Experimental plan.

Parameters	Values
W/C (%)	40
Slump (cm)	15 ± 1
SRA content (% of cement weight)	0, 0.15, 0.30, 0.45, 0.60
Curing temperature (°C)	5, 20, 30, 50

Table 2
Concrete mixture proportions.

W/C (%)	Water (kg/m^3)	Sand–aggregate ratio (%)	SRA/cement (%)	AEW[a]/cement (%)	Absolute volume (l/m^3)			SRA (kg/m^3)
					Cement aggregate	Fine aggregate	Coarse aggregate	
40	175	44	0	0.45	139	282	359	0
			0.15					0.66
			0.30					1.31
			0.45					1.97
			0.60					2.63

[a] AEW: air entraining water reducing agent.

Table 3
Physical properties of cement.

Density (g/cm^3)	Blaine fineness (cm^2/g)	Soundness (%)	Setting time (min.)		Compressive strength (MPa)		
			Initial	Final	3 days	7 days	28 days
3.15	3413	0.08	229	410	23.3	31.1	41.4

Table 4
Physical properties of aggregates.

Aggregates	Density (g/cm^3)	Fineness modulus	Absorption (%)	Unit weight (kg/m^3)	Amount passing (0.08 mm sieve) (%)
Fine aggregate	2.57	2.7	1.83	1.470	1.8
Coarse aggregate	2.63	6.9	0.62	1.577	0.3

Table 5
Composition of SRA.

Ingredient	Basis	Appearance
White sugar	Sucrose	White grain
Viscosity modifying agent	Poly ethylene oxide	White grain
Air-entrained agent	Sodium lauryl sulfate	Aqueous

Table 6
Physical properties of SRA.

Density (g/cm^3)	Viscosity (MPa s)	pH (20 °C)	Surface tension (mN/m)	Sucrose (w/v%)
1.23	14	7.5	59.1	47.8

for overcoming the loss of air content were added at a specific ratio. The optimal mixing ratio of each agent was fixed at 1 (white sugar solution diluted with water at 1/1000) to 1 (PEO solution diluted with water at 5/1000) to 0.005 (AE agent) on the basis of a number of trial batches. The viscosity of the SRA solution was 14 MPa s and the surface tension was 59.1 mN/m. The Composition and physical properties of SRA are listed in Tables 5 and 6, respectively.

3.3. Test methods

Concrete was mixed in a forced-pan-type mixer. A slump test was carried out in accordance with the Korean Industrial Standard (KS) F 2402, and the slump flow was measured 5 min after the slump cone was withdrawn. The air content was measured in accordance with KS F 2421. The setting time was measured by performing the Proctor penetration test according to KS F 2436 (similar to ASTM C 403). Specimens for measuring the setting time were placed in a curing chamber at 5, 20, 35, and 50 °C after casting until final setting.

Compressive strength specimens were prepared using ∅ 100 × 200 mm cylindrical moulds in accordance with KS F 2403, and the compressive strength was measured in accordance with KS F 2405.

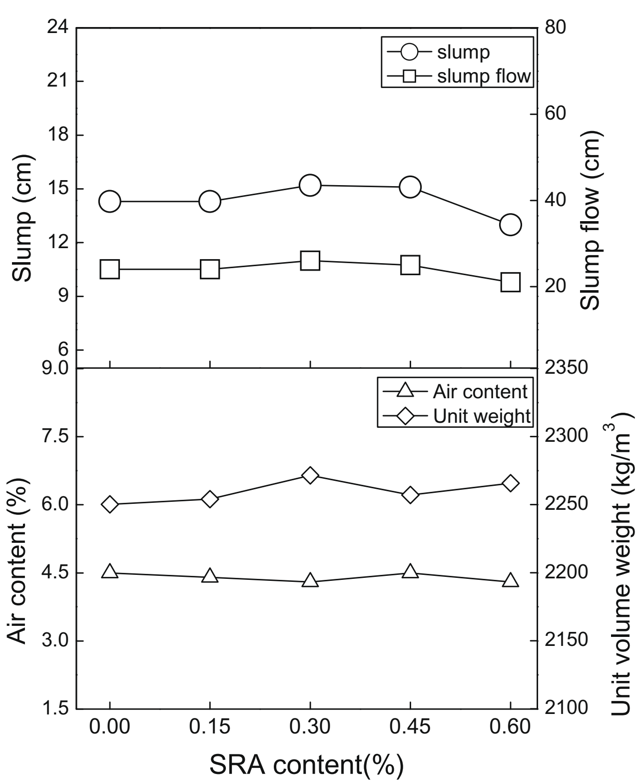

Fig. 1. Physical properties of fresh concrete with SRA contents.

4. Results and discussion

4.1. Fundamental properties of fresh and hardened concrete

Fig. 1 shows the relationship among the slump, slump flow, air content and unit volume weight, and SRA content. The slump and slump flow were constant as the SRA content increased to 0.45%. The use of more than 0.45% SRA resulted in slight increases in

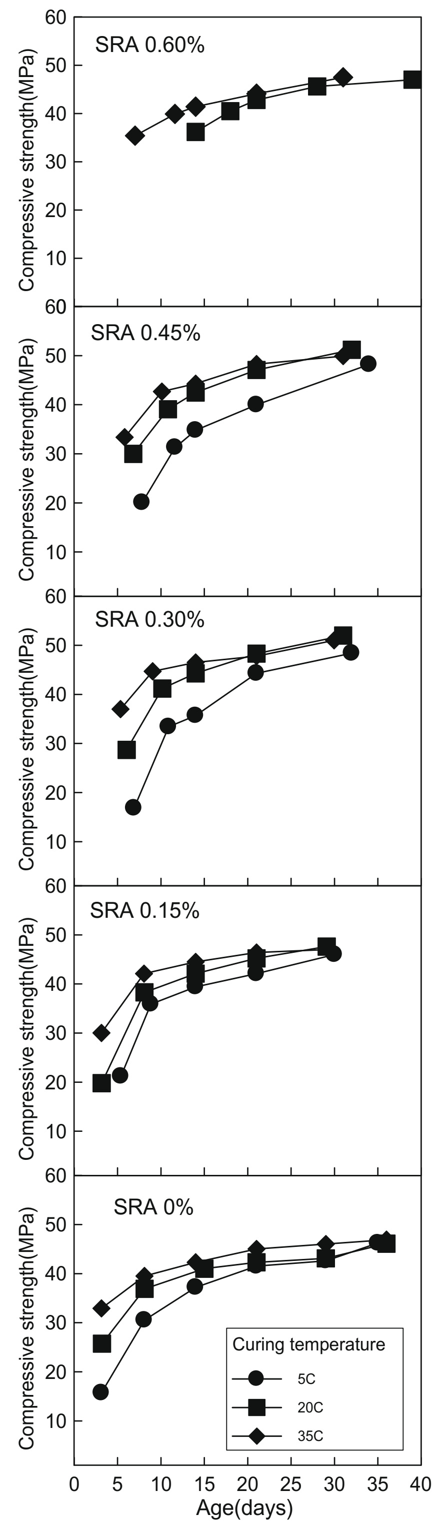

Fig. 2. Compressive strength under various curing temperatures and SRA contents with age.

the slump and slump flow. The air content did not change considerably with an increase in the SRA content. The unit volume weight was inversely proportional to air content.

Fig. 2 shows the relationship between the compressive strength and the age. Generally, at 3 days and 7 days and also at 28 days, with increasing SRA content, the compressive strength of concrete increased by as much as 5–8% as compared to that of conventional concrete. However, in the case of a curing temperature of 5 °C, an increase in the SRA content in concrete resulted in a decrease in the compressive strength at an early age, owing to the effect of low temperature. Moreover, there was insufficient strength recovery at 28 days. Unfortunately, because of the absence of strength data for concrete with 0.6% SRA at 5 °C and with any SRA content at 50 °C, no analysis was carried out. It was found that at a curing temperature of 35 °C, the compressive strength of concrete containing SRA was higher than that of conventional concrete by as much as 20% at 28 days.

4.2. Setting properties

The relationships between initial and final setting times of concrete for various SRA contents and curing temperatures are shown in Fig. 3. Increasing the SRA content led to considerable retardation of the initial and final sets. This was probably because sugar, which is the main ingredient of SRA, was adsorbed onto surfaces of the hydrating cement particles and hydration product, resulting in a temporary barrier to further hydration for a long period (although the mechanism of the retardation of cement hydration by sugar is only partly understood and controversial) [7].

When the SRA content exceeded 0.45%, the difference in setting time with curing temperature was larger than that in conventional concrete. This suggests that it is necessary to consider the temperature condition when using SRA. In addition, when the SRA content was 0.6%, considerable setting time retardation was observed, and as a result, the final set was around 10 days at a curing temperature of 20 °C and was not even measured over 2 weeks at 5 °C. This was probably due to the combined effect of the excessively high SRA content and low curing temperature.

With regard to the effect of temperature on the setting of concrete containing SRA, an increase in the curing temperature resulted in a decrease in the retardation of concrete containing SRA. This was due to the faster formation of CH nuclei, which re-

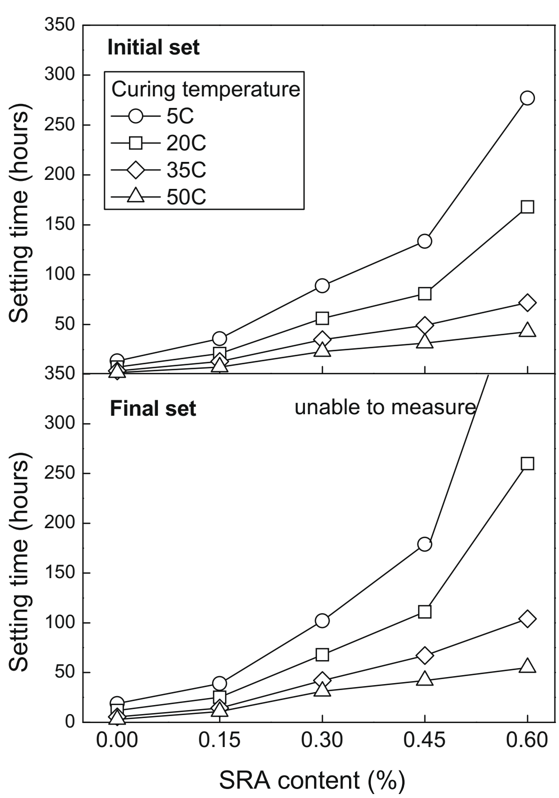

Fig. 3. Relationship between setting time and SRA content under various curing temperatures.

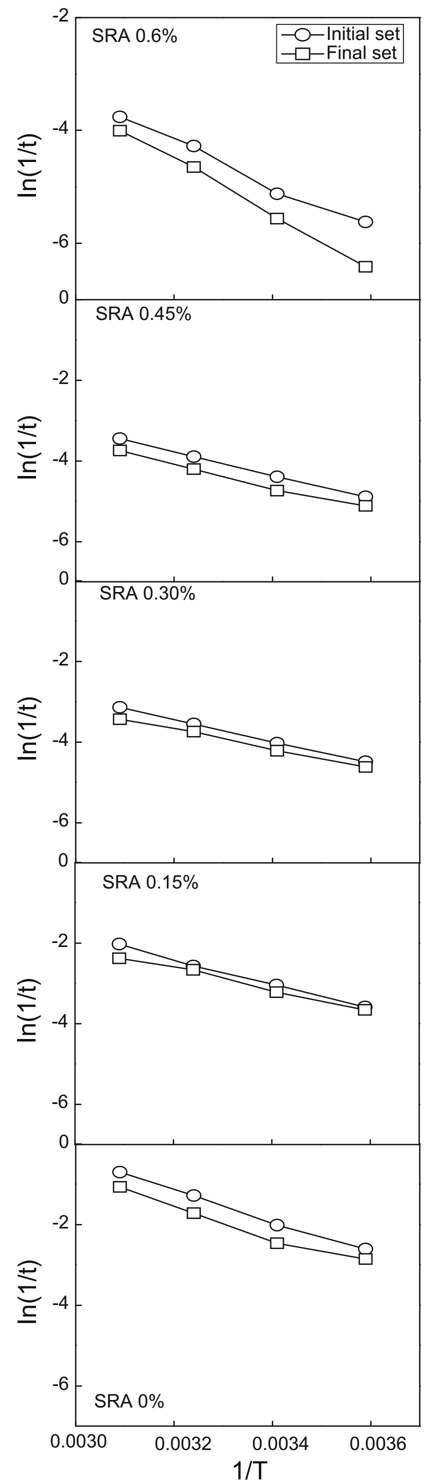

Fig. 4. Relationship between $\ln(1/t)$ and $1/T$ based on Arrhenius function.

sulted in the overcoming of the retardation barrier. After the retardation barrier was broken, the reaction was diffusion controlled [7,21,22].

4.3. Determination of E_a according to SRA content

Fig. 4 shows the relationship between $\ln(1/t)$ and $1/T$ for various SRA contents. To apply maturity to the estimation of the setting time, the Y-axis should be $\ln(k_T)$ instead of $\ln(1/t)$ and the X-axis should be the inverse of absolute temperature $(1/T)$, and a linear relationship between $\ln(1/t)$ and $1/T$ should be determined through regression analysis. In general, $\ln(1/t)$ and $1/T$ had a linear relationship regardless of the SRA content.

Table 7
Regression analysis results for Arrhenius plot according to SRA contents.

SRA (%)	Regression coefficient		
	A	Q (E_a/R)	Correlation coefficient
0.00	11.27	3878.34	0.976
	10.12	3646.93	0.997
0.15	7.42	3070.22	0.990
	5.83	2645.48	0.995
0.30	5.23	2712.80	0.996
	4.07	2423.53	0.994
0.45	5.45	2884.23	0.991
	4.80	2776.43	0.989
0.60	11.12	4886.52	0.956
	8.13	3849.22	0.978

Table 8
Calculated apparent activation energy with SRA content.

SRA (%)	Apparent activation energy (kJ/mol)	
	Initial set	Final set
0.00	32.2	30.2
0.15	25.5	21.9
0.30	22.6	20.2
0.45	23.9	23.1
0.60	31.9	40.6

Table 7 shows the results of linear regression analysis using the Arrhenius function at the initial and final sets. The slope of the regression equation is E_a/R (where R is the gas constant, equal to 8.341 J/mol K), and E_a is calculated by multiplying the slope by R.

Table 8 shows values of E_a calculated from the analysis results shown in Table 7. E_a for conventional concrete was 32.2 kJ/mol at the initial set and 30.2 kJ/mol at the final set. These values are similar to the value of 33.5 kJ/mol suggested by Freisleben-Hansen and Pedersen, but they are slightly lower than the value of 37.6 kJ/mol suggested by Pinto or the value of 40–45 kJ/mol suggested by ASTM C 1074. This is due to the mixture condition and the presence of the chemical admixture. Accordingly, the E_a value during the setting time obtained using the modified Arrhenius function is considered similar to the E_a value obtained from ASTM C 1074. This implies that the maturity function using E_a is applicable to the estimation of the setting time.

In the case that SRA is added, on the other hand, E_a is generally calculated to be between 20 and 30 kJ/mol, which is lower than that in the case of conventional concrete. For an SRA dosage of 0.15%, E_a is 25.5 kJ/mol at the initial set and 21.9 kJ/mol at the final set. Up to an SRA dosage of 0.45%, E_a is around 20.2–23.1 kJ/mol. The deviation of the E_a value for the SRA dosages of 0.15–0.45% is no more than 3 kJ/mol, which is marginal. However, the addition of SRA decreases E_a by as much as 7–10 kJ/mol.

More interestingly, E_a increases when the SRA content is 0.60%. The effect of SRA dosage on E_a observed in this study is not in complete agreement with the effect of a chemical agent on E_a reported in a previous study [24,25]. Lachemi and Hossain [24] presented the effect of retarder dosage on E_a and stated that unique values of E_a could characterize the concrete mixture independently of the retarder dosage, although he did not explain why this is possible. However, from the viewpoint of a chemical reaction, it may be due to the fact that E_a is independent of chemical agents such as accelerators or retarders in a side chemical reaction or at least it is not affected by the use of accelerators or retarders, because the use of a chemical agent does not change the crystal structure and/or compound of concrete.

Meanwhile, other researchers obtained different E_a values for different cementitious materials and chemical agents. Because of the change in mechanical behavior for different dosages of the

Table 9
Equivalent age with SRA contents.

SRA (%)	Curing temperature (°C)	Setting time (h)				Equivalent age (h)			
		Initial	Final	Initial set	Average	Standard deviation	Final set	Average	Standard deviation
0.00	5	13.6	18.9	6.6	6.9	0.36	9.6	10.2	1.13
	20	7.5	11.8	7.5			11.8		
	35	3.6	5.6	6.8			10.3		
	50	2.0	2.9	6.8			9.2		
0.15	5	36.0	39.0	20.4	20.8	0.74	23.9	24.0	1.37
	20	21.0	25.2	21.0			25.3		
	35	13.1	14.3	21.8			22.2		
	50	7.6	10.8	20.1			24.8		
0.30	5	89.0	102.0	54.0	54.8	1.01	65.2	65.8	2.27
	20	56.3	68.0	56.3			68.0		
	35	35.0	42.0	54.9			62.8		
	50	23.0	31.1	54.3			67.0		
0.45	5	133.5	179.0	78.5	79.4	1.17	107.3	106.4	4.03
	20	81.0	111.0	81.0			111.0		
	35	49.3	67.0	79.6			106.2		
	50	31.5	42.0	78.5			101.2		
0.60	5	277.0	614.0	136.4	146.5	14.8	249.6	250.7	11.8
	20	168.0	260.0	168.0			260.0		
	35	72.0	104.5	136.4			234.3		
	50	43.0	55.0	145.5			258.9		

set retarding agent, E_a can vary while predicting the setting time. In this study, E_a was determined by mechanical means in accordance with ASTM C 1074. To obtain more accurate results and explain the variation in E_a due to SRA dosage, it is suggested that the values of E_a could be expected in view of the heat of hydration based on calorimetric means insofar as the effect of the SRA is not clearly understood.

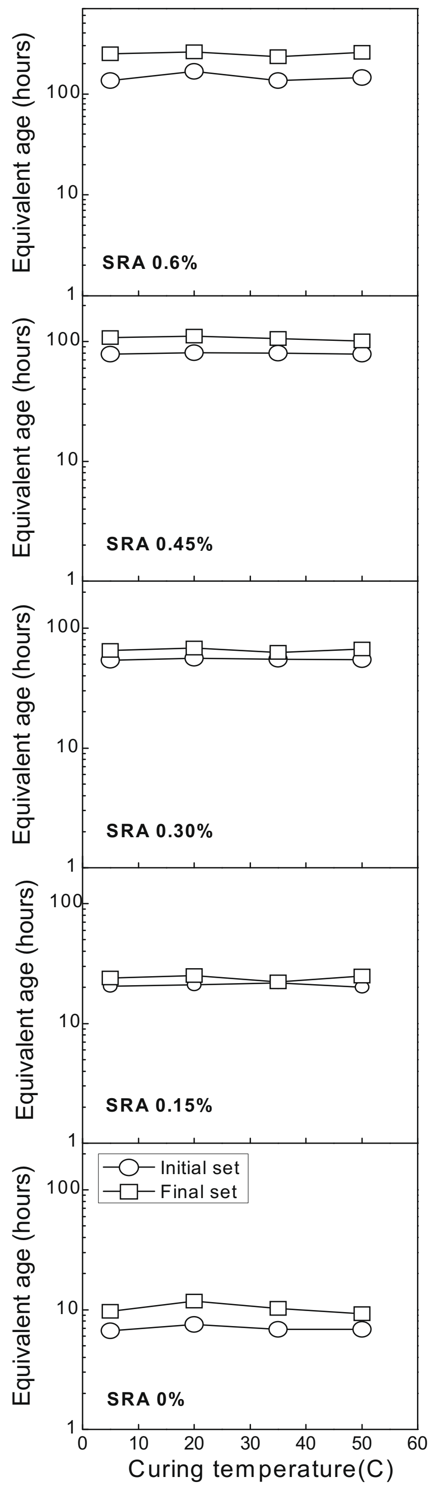

Fig. 5. Relationship between equivalent age and curing temperatures with SRA contents.

4.4. Estimation of setting time by applying equivalent age

Table 9 shows the equivalent ages at the initial and final sets according to curing temperature, which is obtained by applying E_a to Eq. (3) derived by Freisleben-Hansen and Pedersen. Fig. 5 shows the relationship between the equivalent age and curing temperatures depending on SRA contents at the initial and final sets. In general, the equivalent age is constant for different SRA contents regardless of the curing temperature. This result is consistent with the concept of maturity and indicates that maturity can be applied to the estimation of the setting time.

For conventional concrete, the estimated equivalent ages were 6.96 and 10.23 h at the initial and final sets, respectively, 20.85 and 24.08 h for an SRA content of 0.15%, 54.8 and 65.8 h for an SRA content of 0.30%, 79.4 and 106.4 h for an SRA content of 0.45%, and 146.5 and 250.7 h for an SRA content of 0.60%. It was found that the equivalent age increases with an increase in the SRA content.

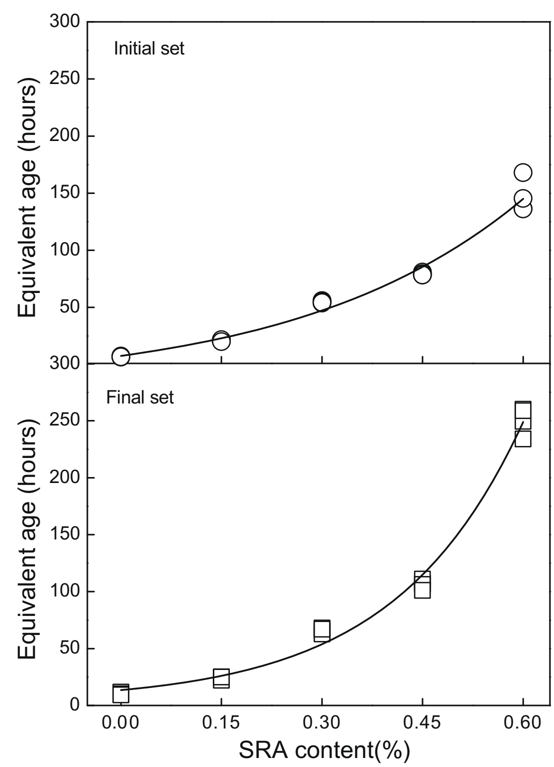

Fig. 6. Effect of SRA contents on equivalent age at initial and final set.

Table 10
Calculated setting time with SRA contents.

SRA (%)	Setting time	Setting time (h)			
		5 °C	20 °C	35 °C	50 °C
0.00	Initial	14.2	6.9	3.6	2.0
	Final	20.8	10.2	5.3	2.9
0.15	Initial	36.7	20.8	12.5	7.8
	Final	42.4	24.0	14.5	9.1
0.30	Initial	90.4	54.8	34.9	23.2
	Final	108.4	65.7	41.9	27.8
0.45	Initial	135.0	79.4	49.1	31.8
	Final	181.0	106.4	65.9	42.6
0.60	Initial	297.6	146.6	77.4	43.2
	Final	508.9	250.7	131.3	74.1

Fig. 6 shows the equivalent ages at the times of the initial and final sets for different SRA contents. The equivalent age according to the SRA content can be estimated using the regression equations (Eqs. (5) and (6)) presented on the graph.

$$t_e = 8.85 \cdot e^{4.954 \cdot s} (R^2 = 0.960) \quad (5)$$

$$t_e = 11.0 \cdot e^{5.258 \cdot s} (R^2 = 0.988) \quad (6)$$

where t_e is the equivalent age (h) and s is the SRA content (%).

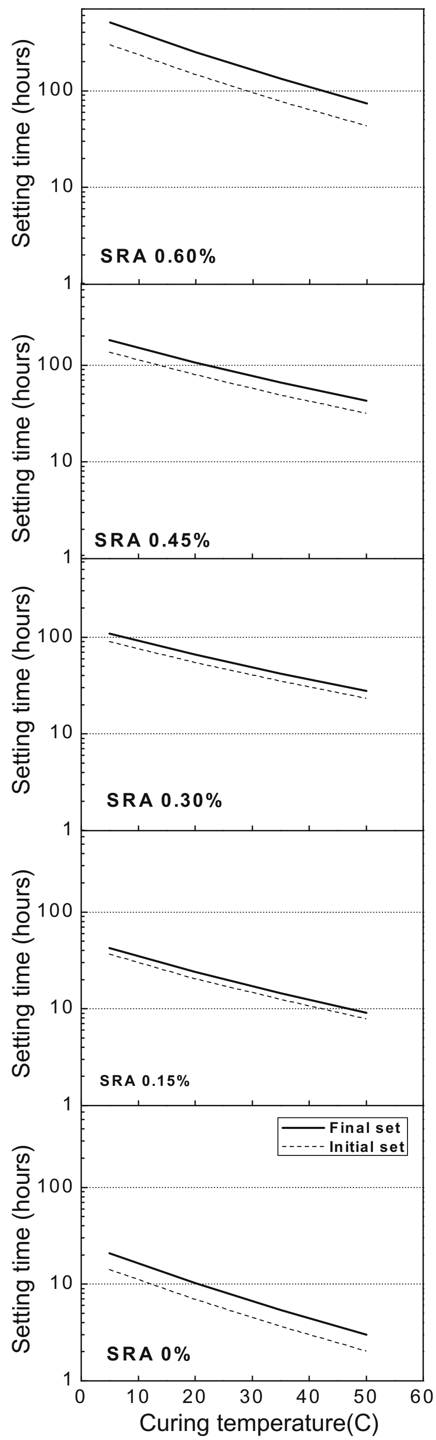

Fig. 7. Estimation of setting time according to curing temperatures and SRA contents.

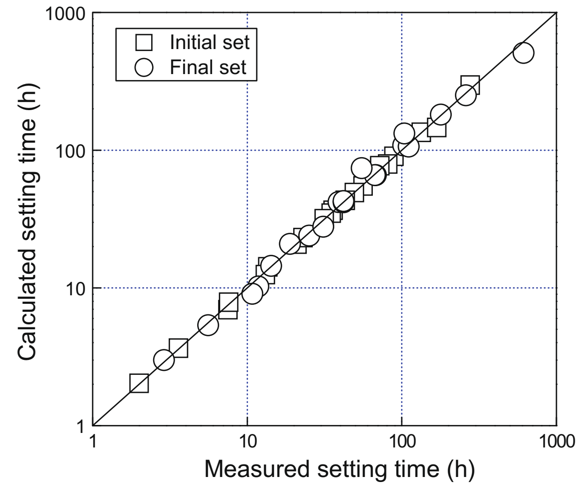

Fig. 8. Comparison of calculated setting time with measured setting time.

Table 10 and Fig. 7 show the times of the initial and final sets estimated from the equivalent age according to the SRA content. The setting time was calculated using E_a and the curing temperature from the function of the equivalent age. In general, the calculated setting time increased with a decrease in curing temperature and with an increase in the SRA content.

Fig. 8 shows a comparison of the measured setting time with the calculated setting time. The measured and estimated values are in good agreement. Hence, it is proved that the procedure investigated in this study can be used for estimating the setting time of concrete containing SRA.

5. Conclusions

In this study, we have investigated the applicability of the maturity concept to the estimation of the setting time of concrete containing SRA contents ranging from 0% to 0.60% of cement weight. From the results obtained in this study, the following conclusions are drawn.

(1) With an increase in the SRA content and a decrease in curing temperature, the initial and final setting times are delayed considerably, and particularly when the SRA content is 0.6%, the setting time increases significantly and the final set is measured at around 10 days at a curing temperature of 20 °C and is not even measurable in two weeks at 5 °C. This is due to the combined effect of excessively high SRA content and low curing temperature.
(2) E_a values at the initial and final sets estimated using the Arrhenius function vary with SRA content. They are estimated to be 30–35 kJ/mol for conventional concrete, which is similar to or slightly lower than the results of a previous study, but are in the range 20–40 kJ/mol in concrete containing SRA, which is lower than that for conventional concrete.
(3) When the estimated E_a is applied to Freisleben-Hansen and Pedersen's equivalent age function, E_a remains constant regardless of the curing temperature. This implies that the concept of maturity can be applied to the estimation of the setting time.
(4) A comparison between the estimated setting time and the measured setting time reveals that there exists good agreement between them. The estimation model for predicting the setting time of concrete containing SRA is presented as Eqs. (5) and (6). The proposed model can be used to accurately estimate the equivalent ages at the initial and final settings.

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