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Prediction of Temperature and Aging Effects on the Properties of Concrete

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ABSTRACT

For the sustainable concrete structures, it is necessary to exactly predict the material properties of concrete with age and each place of structures.
This paper investigates prediction models estimating the temperature and aging effects on the hydration properties of concrete, such as the compressive strength, the splitting tensile strength, the elastic modulus, and the autogenous shrinkage. A prediction model is suggested on the basis of an equation that is formulated to predict the compressive strength. Based on the assumption that the apparent activation energy is a characteristic property of concrete, a prediction model for the compressive strength is applied to hydration-related properties. The hydration properties predicted by the model are compared with experimental results, and it is concluded that the prediction model properly estimates the splitting tensile strength, elastic modulus, and autogenous shrinkage as well as the compressive strength of concrete.

Keywords. Temperature; Aging; Hydration properties; Apparent activation energy; Prediction model

INTRODUCTION

Concrete is an aging material, and the hydration-related properties of concrete change with time. Meanwhile, the heat of hydration in mass concrete structures creates a temperature gradient between the inner and surface. This temperature gradient affects the properties of the concrete, i.e., the compressive strength, elastic modulus, splitting tensile strength, and autogenous shrinkage. Also, the temperature variations caused by cold-weather or hot-weather conditions have the same influence on concrete. Hydration properties such as the compressive strength, elastic modulus, splitting tensile strength, and autogenous shrinkage are factors that must be considered in the design and construction of concrete structures. Specifically, an evaluation of the thermal cracking of a mass concrete structure requires an estimation of the elastic modulus and tensile strength of early-age concrete with the temperature. Therefore, it is very important to estimate the properties of concrete according to different temperature and aging factors (Abdel-Jawad 2006, Alexander and Taplin 1962, Freiesleben Hansen and Pedersen 1977, Gardner 1990, Kim *et al*. 1998, Kjellsen and Detwiler 1993, Lew and Reichard 1978, Zhang *el al*. 2008).
Many existing evaluations of the influence of temperature and aging on the hydration properties focus primarily on the compressive strength, while only a few prediction models

are available for estimating the elastic modulus and splitting tensile strength (Chengju 1989, Gardner 1990, Kim *et al.* 2001, Tank and Carino 1991). To evaluate the validity of a prediction model, not only the compressive strength but also other properties which are related to the hydration process should be estimated using the prediction model. Among several existing models, the model proposed by Kim *et al.* (2001), which is based on a new apparent activation energy function, was reported to overcome the shortcomings of previous prediction models.

The objectives of this study are to evaluate the validity of the prediction model which is proposed by Kim *et al.* (2001) for estimating the hydration-related properties such as the splitting tensile strength, elastic modulus, and autogenous shrinkage as well as the compressive strength of concrete

PREDICTION MODEL

Although the Arrhenius law is generally accepted (Freiesleben Hansen and Pedersen 1977, Han and Han 2010, Jonathan *et al*. 2011, Nielsen 2007, Viviani *et al*. 2007, Waller *et al*. 2004) as the most suitable rate function for hydration of concrete among several prediction models, several researches (Chanvillard and D'Aloia 1997, Jonasson 1985, Kjellsen and Detwiler 1993) about the shortcomings of the Arrhenius equation have been reported.

A prediction model was proposed by Kim *et al.* (2001) to estimate the compressive strength development with temperature and aging. This model mitigated the shortcomings of previous models and reasonably approximated the experimental results pertaining to the compressive strength. This paper investigates the effectiveness of this model as a tool for predicting the hydration properties like the splitting tensile strength, elastic modulus, and autogenous shrinkage as well as the compressive strength of concrete. The following equation is the prediction model proposed by Kim *et al.* (2001).

$$\frac{S}{S_u} = 1 - \frac{1}{\sqrt{1 + A\sum_{i=1}^{n}\left[e^{-\frac{E_o}{RT_i}e^{-\alpha t_i}} + e^{-\frac{E_o}{RT_i}e^{-\alpha t_{i-1}}} \right](t_i - t_{i-1})}} \tag{1}$$

where, S is the compressive strength, S_u is the limiting compressive strength, A is a constant, R is the gas constant and equal to 8.3144 J/K·mole, T_i is the curing temperature at time step i (K), E_o is the initial apparent activation energy (J/mole), α is a constant, t_{i-1} is the initial age of time step i (days) and t_i is the final age of time step i (days). This equation involves four unknown parameters, t_o, E_o, α, and A.

After the prediction model was introduced, the application of the model has been investigated by several researchers (Kim *et al.* 2002, Chu *et al.* 2012). Kim *et al.* (2002) applied the model to predict the elastic modulus and splitting tensile strength as well as the compressive strength of concrete. Reasonably good agreement was shown between the predicted results and the measured results. However, the apparent activation energy function was determined using the results of the compressive strength only. While Chu *et al*. (2012) reported that the prediction model could also be applied to predict the autogenous shrinkage of concrete, there has been no attempt to apply the prediction model to as determination of all hydration-related properties (compressive strength, splitting tensile strength, elastic modulus, and autogenous shrinkage) using the same apparent activation energy.

The apparent activation energy can be interpreted from the two standpoints of a 'micro' level and a 'macro' level. At the macro-level, the apparent activation energy is related to the increasing development rate of the compressive strength. Thus, if the model is applied to

other properties for which the increasing rate is different from that of the compressive strength, the regression curves will have different levels of apparent activation energy according to different properties. On the other hand, the apparent activation energy at the micro-level is a function of the degree of cement hydration. Thus, if the apparent activation energy is considered as a characteristic property of concrete at the micro-level, the apparent activation energy is a constant value in all types of hydration-related properties. Many researchers (Chanvillard and D'Aloia 1997, Riding et al. 2011, Kada-Benameur *et al.* 2000, Kjellsen and Detwiler 1993, Wang *et al*. 2007) have proposed that the apparent activation energy is related to the hydration process of cement. Therefore, it can be assumed that the apparent activation energy is a characteristic property of concrete and that it has a constant value in all types of hydration-related properties.

The increasing rates of the splitting tensile strength, elastic modulus, and autogenous shrinkage are dissimilar to that of the compressive strength, and the dissimilarity must be considered in Eq. (1). The proportional constant A in Eq. (1) can simulate the differences in the increasing rate, even when the apparent activation energy is identical to different hydration-related properties. Therefore, it can be assumed that the difference in the increasing rate is able to be estimated by modifying the constant A with hydration-related properties. In this paper, based on the previous assumption, experimental results of hydration-related properties like the compressive strength, elastic modulus, splitting tensile strength, and autogenous shrinkage are analyzed using the prediction model, Eq. (1).

PREDICTION OF HYDRATION-RELATED PROPERTIES OF CONCRET

Experiments. For the application of the prediction model, the experimental results reported in previous research (Chu *et al*. 2012) are analysed. Table 1 shows the mix proportion used in the experiments. Ordinary Portland cement (ASTM type I) and silica fume are used as cementitious materials. In this experiment, the autogenous shrinkage under an isothermal curing condition (20, 30, and 40℃) was measured. Additional 100×200mm cylindrical specimens were cast along with the shrinkage specimens of 100×100×400mm to investigate the development of the mechanical properties of concrete like the compressive strength, elastic modulus, and splitting tensile strength of the concrete under different isothermal curing conditions (20, 30, and 40℃).

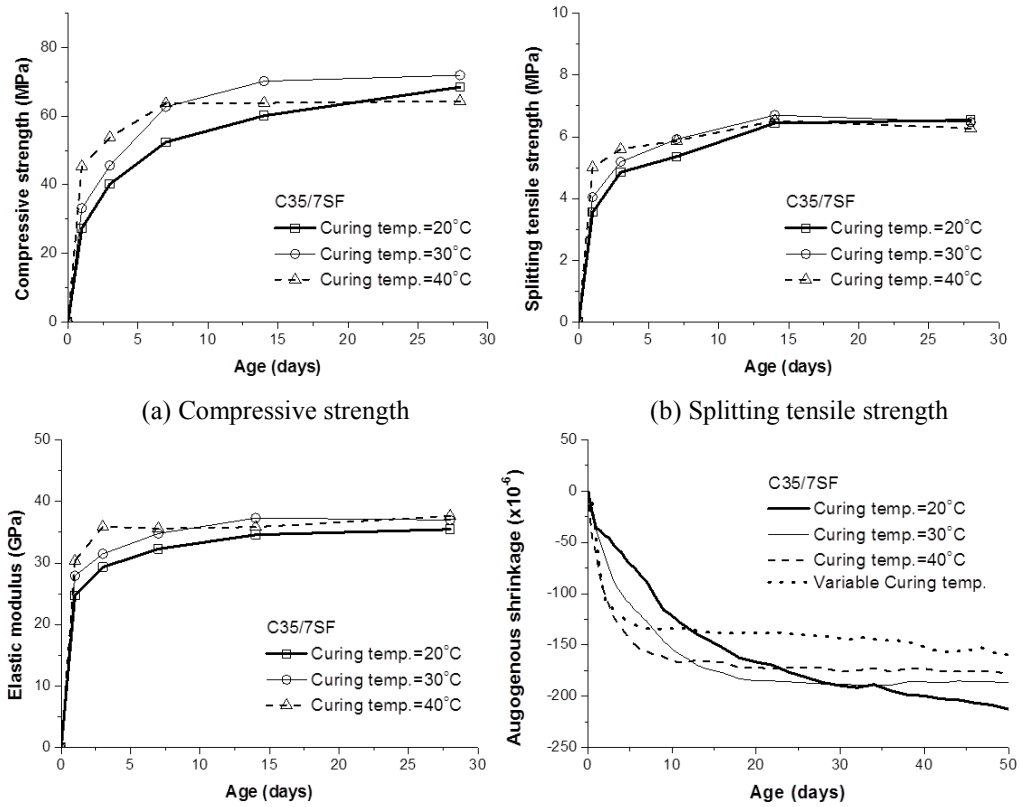
Table 1 Mix proportion

Mix ID	Curing temperature, (℃)	w/cm	*S*/a	Unit weight (kg/m^3)					Ad[C] (%)
				W	*C*	SF[a]	*S*	*G*[b]	
C35/7SF	20,30,40	0.35	0.40	175	465	35	665	1007	1.0

[a] Silica fume, 7% of total weight of cementitious materials
[b] Maximum aggregate size of 20mm
[c] Superplasticizer (ASTM Type-F high range water-reducing admixture), % of total cementitious materials

Fig. 1 shows the experimental results of each property of concrete specimens. As shown in Fig. 1, the one- and three-day compressive strength levels increased with an increase in the curing temperature. However, this tendency was reversed with aging. The 28-day compressive strength of concrete cured at 40℃ is the lowest. These results suggest that

concrete subjected to a high temperature at an early age attains a higher early-age compressive strength but a lower later-age compressive strength. Alexander and Taplin (1962) referred to this phenomenon as the "crossover effect". The same phenomenon also arises in the splitting tensile strength, elastic modulus, and autogenous shrinkage with increasing curing temperatures. However, the crossover effect of the splitting tensile strength and the elastic modulus is not as obvious as that of the compressive strength and autogenous shrinkage. This is due to the differences between the rates of increase for each property.



(a) Compressive strength (b) Splitting tensile strength

(c) Elastic modulus (d) Autogenous shrinkage

Fig. 1 Experimental results of hydration-related properties

Application of prediction model. As mentioned previously, the increasing rates of the splitting tensile strength, elastic modulus, and autogenous shrinkage are dissimilar to that of the compressive strength. This dissimilarity should be considered in Eq. (1). The difference in the increasing rate can be estimated by modifying the constant *A* with determined properties. Following previous research (Kim *et al*. 2001), an *A* value in Eq. (1) of 1.0×10^7 is determined as the reference for the compressive strength. From the relationship between the relative compressive strength and each property, the *A* value of each property can be determined. The values of the compressive strength, splitting tensile strength, elastic modulus, and autogenous shrinkage are 1.0×10^7, 3.0×10^7, 5.0×10^7, and 0.3×10^7, respectively.

Table 2 tabulates the regression results of test results for the determination of parameters in the prediction model, Eq (1). Based on the results, the variation of each parameter with the curing temperature is presented and following general equations is obtained.

Table 2 Regression results of parameters in the prediction model

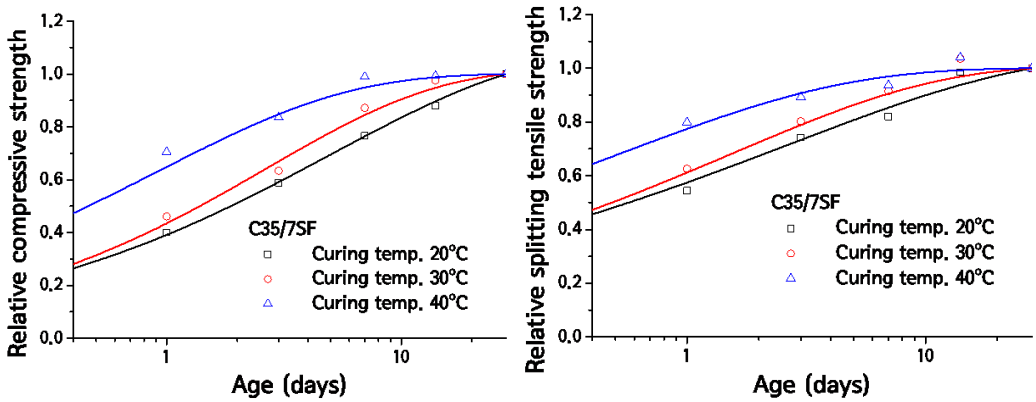
Curing temperature (℃)	E_o (J/mole)	α	t_o
20	41083	0.0048	0.22
30	40861	0.0072	0.11
40	39917	0.0102	0.00

$$E_o = 42,369 - 58T^c \text{ J/mole} \quad (2)$$

$$\alpha = 0.00025T^c \quad (3)$$

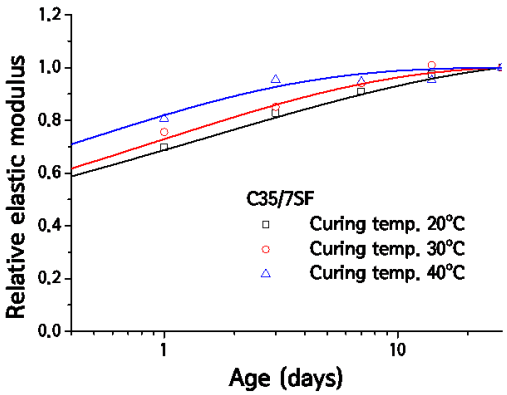
$$t_o = 0.440 - 0.011T^c \quad (4)$$

Fig. 2 depicts the predicted curves as well as the experimental results of the hydration-related properties, i.e., compressive strength, splitting tensile strength, elastic modulus, and autogenous shrinkage. In this figure, the scattered points denote the experimental results and the solid lines denote the predicted values. The differences between the calculated value and the experimental result likely arise because the regression results are based on a small number of test results excluding the results at a later-age. However, as shown in Fig. 3, the error range is less than ±10 percent, which reflects that the prediction model properly estimates the hydration-related properties of concrete.

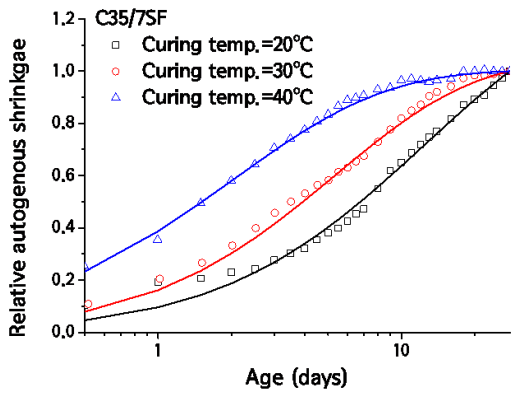


(a) Compressive strength

(b) Splitting tensile strength



(c) Elastic modulus



(d) Autogenous shrinkage

Fig. 2 Predicted values and experimental results

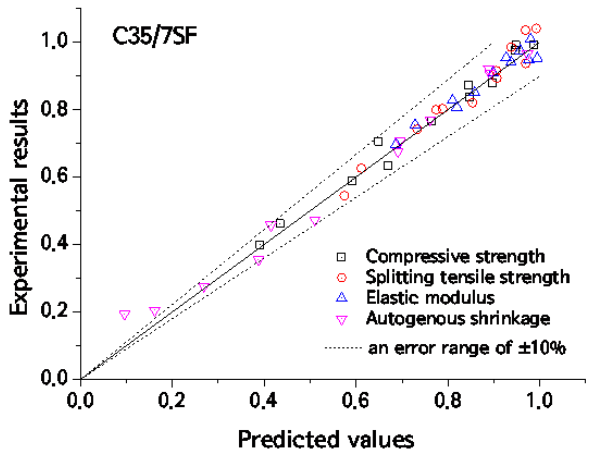


Fig. 3 Comparison of predicted values and experimental results

RELATIONSHIPS BETWEEN SPLITTING TENSILE STRENGTH AND COMPRESSIVE STRENGTH OR ELASTIC MODULUS AND COMPRESSIVE STRENGTH

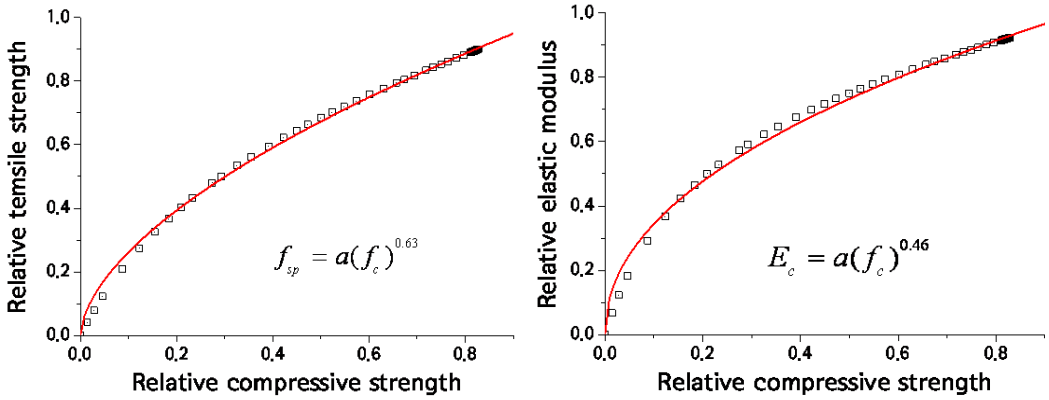
In many existing codes, i.e., ACI 318 (American Concrete Institute 1999) and CEB-FIP model code 1990 (CEB-FIP 1993), a relationship between the splitting tensile strength and the compressive strength or the elastic modulus and the compressive strength are presented by following equations.

$$f_{sp} = a \times f_c^b \tag{5}$$

$$E_c = a \times f_c^b \tag{6}$$

where, f_{sp} is the splitting tensile strength, E_c is the elastic modulus, f_c is the compressive strength, a and b are empirical constants.

In Eq. (5) and Eq. (6), a dissimilarity of increasing rate between the compressive strength and each property is considered by the value of b. ACI 318 suggests b values of 0.50 and 0.50 for the splitting tensile strength in Eq. (5) and the elastic modulus in Eq. (6), respectively. While, CEB-FIP model code 1990 suggests b values of 0.67 and 0.33 for the splitting tensile strength in Eq. (5) and the elastic modulus in Eq. (6), respectively.
The value of b is closely related to the value of A in Eq. (1). In the previous section, different values of A for each property were determined based on a regression analysis of the experimental results. The values of the compressive strength, splitting tensile strength, and elastic modulus were 1.0×10^7, 3.0×10^7, and 5.0×10^7, respectively. To obtain values of b corresponding to determined values of A, the relationship between the relative compressive strength and the relative values of each property were drawn in Fig. 4 (a) and (b). The determined values of b are 0.63 and 0.46 for the splitting tensile strength and the elastic modulus, respectively.
Also, the values of A corresponding to the existing model codes is determined. These values of A are tabulated in Table 3.



(a) Relationship between f_{sp} and f_c (b) Relationship between E_c and f_c

Fig. 12 Relationship between the compressive strength and each property

Table 3 Values of A corresponding to existing model codes

	Model equation	Values of A in Eq. (1)		
		for compressive strength	for splitting tensile strength	for elastic modulus
ACI 318	$f_{sp} = 0.56 f_{ck}^{0.50}$ $E_c = 4,700 f_{ck}^{0.50}$	1.0×10^7	3.7×10^7	3.7×10^7
CEB-FIP 1990	$f_{sp} = 0.30 f_{cu}^{0.67}$ $E_c = 8,480 f_{cu}^{0.33}$	1.0×10^7	2.1×10^7	6.5×10^7

CONCLUSIONS

To investigate the validity of the prediction model, the model is applied to the hydration-related properties of the compressive strength, splitting tensile strength, elastic modulus, and the autogenous shrinkage. Based on results in this paper, the following conclusions were drawn.

1. Based on the assumption that the apparent activation energy is the characteristic property of concrete, a prediction model for compressive strength is applied to other hydration-related properties, i.e., the splitting tensile strength, elastic modulus, and the autogenous shrinkage. The predicted values by the model are compared with experimental results, and good agreement between the predicted values and the experimental results was observed within an error range of ±10 percent.

2. The proportional constant A is determined to predict different hydration-related properties of the compressive strength, splitting tensile strength, elastic modulus, and the autogenous shrinkage. Determined values of A are 1.0×10^7, 3.0×10^7, 5.0×10^7, and 0.3×10^7 for compressive strength, splitting tensile strength, elastic modulus, and autogenous shrinkage, respectively.

3. An empirical constant b in existing model codes, which defines a dissimilarity of increasing rate between the compressive strength and each property, is closely related to

the value of *A* in the prediction model. The values of *A* corresponding to existing model codes are determined.

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