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Concrete Strength Estimating at Early Ages by the Equivalent Age

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Abstract

The strength development of concrete is influenced by temperature and cement type which greatly affect hydration degree of cement. There is not pertinent concrete strength management method in korea. There are several methods for estimating the in-place strength of concrete. One such method is the maturity concept. The maturity concept is based on the fact that concrete gains strength gradually as a result of chemical reactions between cement and water; and for a specific concrete mixture, strength at any age and at normal conditions is related to the degree of hydration. The rate of hydration and, therefore, strength development of a given concrete will be a function of its temperature. Thus, strength of concrete depends on its time-temperature history. The goals of the present study are to investigate a relationship between strength of high-strength concrete and maturity that is expressed as a function of an integral of the curing period and temperature and predict strength of concrete.

Keywords: maturity, equivalent age, strength management, hydration degree, curing temperature, high strength concrete, strength prediction

1. Introduction

Early age strength prediction in concrete is very useful in the reducing of construction cost and the securing of safety. Recent catastrophic construction failures have emphasized the need to estimate in-place strength of concrete during construction of concrete structure. Those are in part related to inadequate concrete strengths when loads are applied to the structure. Early age strength prediction has several practical applications. It can be used to determine safe stripping time, prestress release or post-tensioning time, to monitor strength development, particularly when concreting in cold weather, to check serviceability conditions or compliance and acceptability criteria, to ensure construction safety and, generally to estimate the quality of construction and potential durability.[1)]

It is the aim of this study to improve and develop the strength prediction in high-strength concrete through the investigation of the correlation between the strength of concrete and maturity for its practical application.

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2. Background theory

2.1 Maturity concept

Maturity method has two theoretical assumptions,Nurse-Saul and Arrhenius: the former is that the rate of strength development is a linear function of temperature, and the latter is that the rate of strength development obeys the exponential Arrhenius equation. The function is expressed that the produce of time and temperature could be used to approximate the combined effects of these two factors on strength development.

Even though curing temperature and its period are different within a range of maturity, maturity which is multiplied curing temperature by curing period, has the same strength, if the areas of from time to temperature are the same as shown Fig.1. These experimental results prove that the strength prediction of concrete by maturity is efficient and significant in all ages. Maturity is represented as shown in

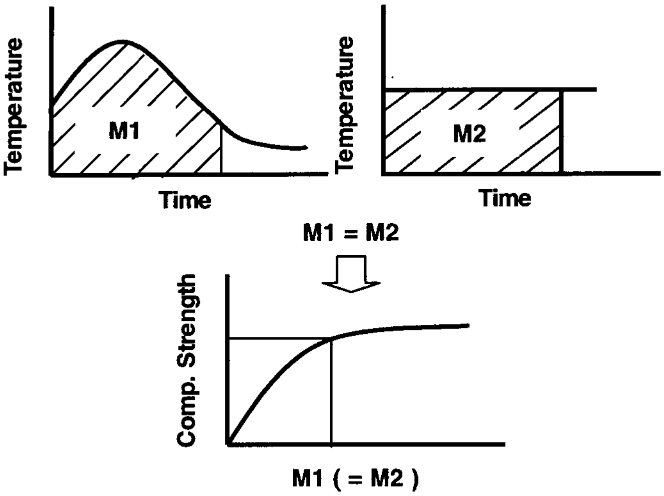


Fig. 1 Maturity concept

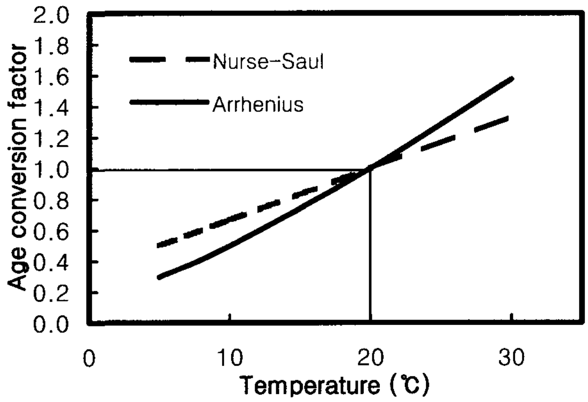


Fig 2. The age conversion factor used to compute equivalent age

Table 1 Age conversion factor vs. curing temperature

Temp. (℃)	T+10	$\frac{T+10}{20+10}$	$\exp[\frac{E}{R}(\frac{1}{Ts}-\frac{1}{Ta})]$
0	10	0.333	0.151
5	15	0.500	0.292
25	35	1.167	1.260
30	40	1.333	1.574
40	50	1.667	2.408

Table 2 Experimental factors and level

Experimental part			Analytical part
W/B (%)	Curing temperature(℃)	Item of test	Using functions
35 30	5 10 20 30	Compressive strength	Nurse-Saul → Rastrup Arrhenius → Frielemben Hansen

Formula (1).[2]

$$M = \sum \alpha \Delta t \qquad (1)$$

Here, α represents age conversion factor, and t represents age, that is lapsed time.

2.2 Strength prediction

To predict the strength of structural concrete, the most proper strength prediction formula is needed by maturity through previous experiments, and the temperature of concrete is measured by Maturity meter. The maturity, M to the time of structural concrete, T can be calculated by using measured temperatures, which can be applied for the strength prediction formula to predict the strength of lapsed time, T. By this, the strength of structural concrete is predicted early, which can make prompt and proper decision in mixture proportion and curing method.

Therefore, the strength management of concrete according to the variation of temperature can be done through the strength prediction by maturity.[3]

2.2.1 Age conversion factor by Nurse-Saul Function

The basic maturity formula of Nurse-Saul which is a function of temperature and time is shown in Formula (2).

$$M=\Sum (T-To)\cdot \triangle t \qquad (2)$$

where,

M : maturity (℃ · h or ℃ · day) at age t

T : average temperature of concrete during time interval Δ t

T_0 : datum temperature (generally -10℃)

△t : time interval (hr or day)

Rastrup presents age conversion factor using it as shown in Formula (3)

$$\alpha = \frac{(T-To)}{(Tr-To)} \qquad (3)$$

Tr: reference temperature of equivalent age (℃)

2.2.2 Age conversion factor by Arrhenius Formula

The hardening speed of concrete is affected much by temperature. So to speak, it is accelerated if the temperature is high, and it is delayed if the temperature is low. The equivalent age on the base of it is made by Arrhenius, a type of chemical reaction speed formula in the correlation between the hydration reaction speed of cement according to curing temperature and the revealment of strength. The reaction speed in 20 ℃ is assumed as 1 in the equivalent age. The excellency of it was proved by Freiesleben-Hansen and Pederson. They presented that Arrhenius equation explained the effect of temperature on the strength of concrete in the ranges of from -10 to 80 ℃ more exactly than Saul-Nurse.[4]

Arrhenius Formula is as follows:

Table 3 Material

Cement	Ordinary Potland Cement(O.P.C) gravity : 3.15 Fineness : 3,200 ㎠/g
Fine aggregate	River sand max size : 5 ㎜ Gravity : 2.55, Fineness Modulous(F.M) : 2.72
Coarse aggregate	Crushed stone max size : 19 ㎜ Gravity : 2.57, Fineness Modulous (F.M) : 6.54
Super Plasticizer(S.P)	Principle component : synthetic polymer Gravity : 1.10
Silica Fume(S.F)	Gravity : 2.20 Fineness : 220,000 ㎠/g

Table 4 Mixture proportions of concrete

Kind	W/B (%)	S.P (%)	S/A (%)	Unit water content(kg/m³)	Unit weight (kg/m³)			
					C	SF	S	G
Cylinder	35	2.3	40	160	411	46	693	1047
	30	3.0		140	420	47	710	1073

$$\alpha = \exp[E/R \cdot (1/Ts - 1/Ta)] \qquad (4)$$

Where,

Ta : curing temperature (°K)

Ts : 293 (°K)

E : cement value which is hydration heat as chemical reaction energy inactivation energy (empirical value)

33.5+1.47(20-Ta) KJ/mol (Ta ≤ 20℃)

33.5 KJ/mol (Ta ≥ 20℃)

R : 8.314 J/mol (invariable number of gas)

2.2.3 Comparison of age conversion factor

The age conversion factors are shown in Table 1 and Fig. 2 being calculated by Formula (3) and Formula (4) and compared each other.

The age conversion factor by Nurse-Saul function represents the reaction speed of concrete according to temperature as a linear function. Formula (4) applied by Arrhenius function shows the form of exponential function.

3. Experimental program and method

3.1 Experimental factors and level

The experiments were performed under the condition of the curing temperatures of 5, 10, 20, and 30 ℃ as shown in Table 2 with the high-strength concretes of water-binder ratio(W/B)30 % and 35 %, to get the exact strength prediction data. The functions by Nurse-Saul and Arrhenius were used as the equivalent age functions for the prediction of compressive strength through the correlation of maturity and the strength of high-strength concrete.

3.2 Used materials

The materials used in the experiments are shown in Table 3.

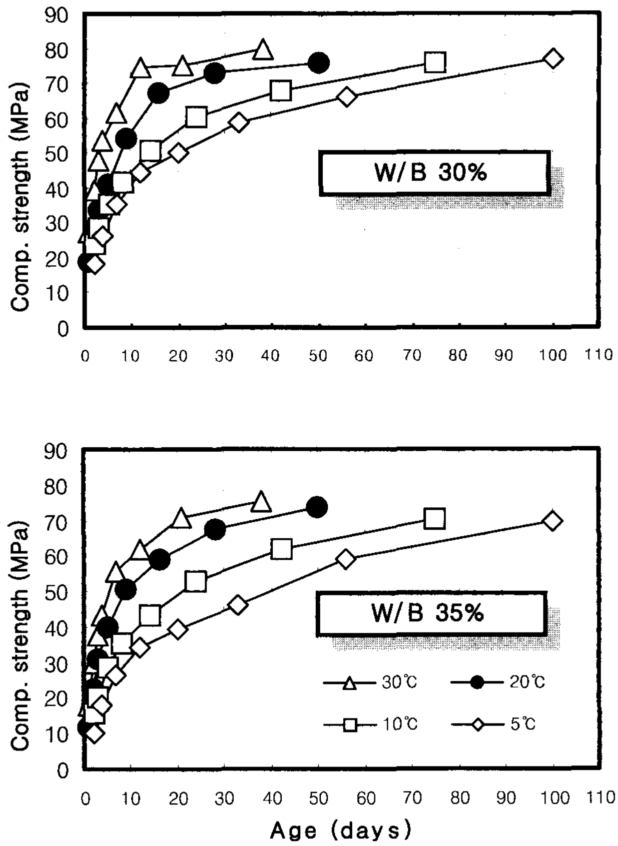


Fig 3. Compressive strength according to age

3.3 Mixture proportion of concrete

The mixture proportion of high-strength concrete used in the experiments are shown in Table 4.

3.4 Experimental methods

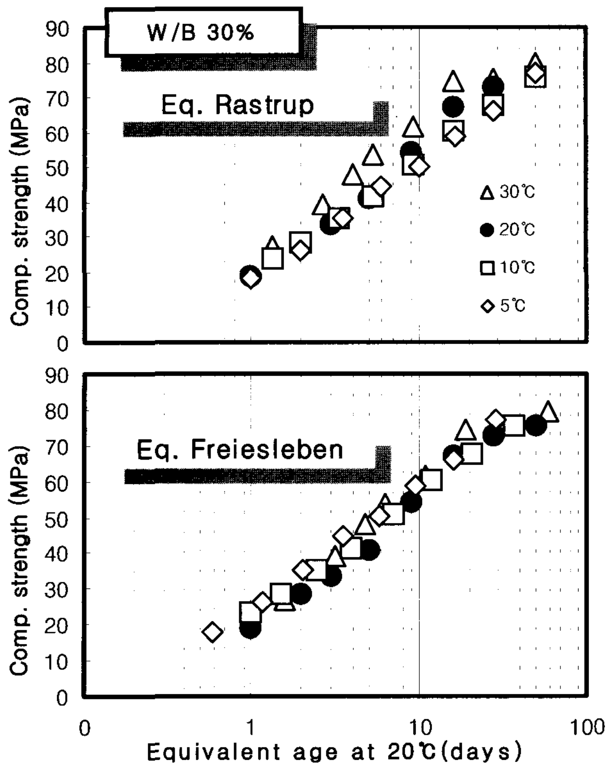
The experiments were performed on the base of Korean Standard and other standards. The temperature of concrete was measured with Thermocouple connected with Maturity Meter.

4. Test results and analysis

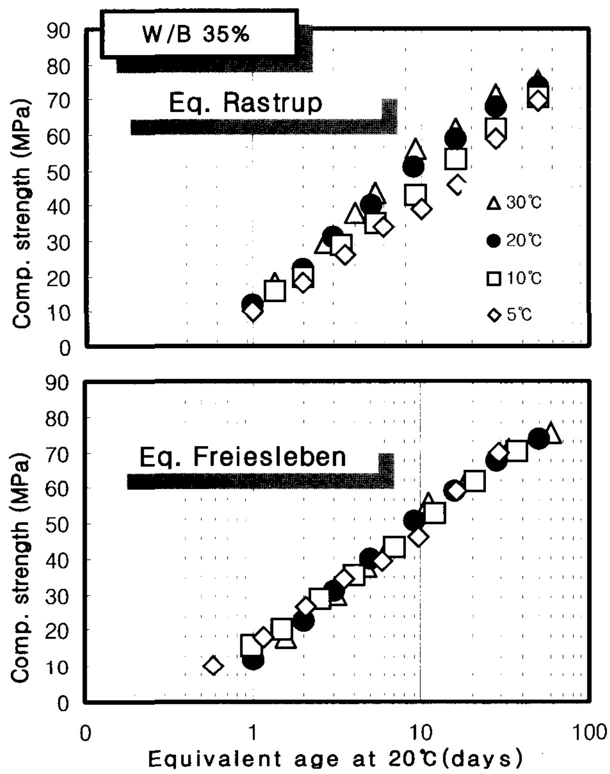
4.1 Strength development in high-strength concrete

Fig. 3 shows each compressive strength in each curing temperature according to ages. In the same age, W/B 30 % has higher revealment of strength than W/B 35 %. In early age, strength is getting higher as curing temperature is higher, and the strengths according to ages are very different according to curing temperatures.

4.2 Correlation of maturity with strength, and Its application



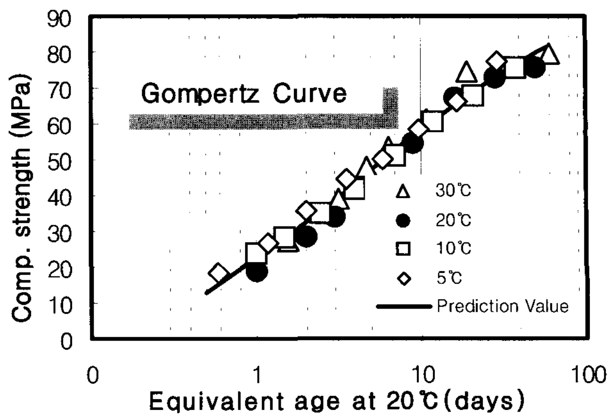
(a) Maturity function (W/B-30 %)



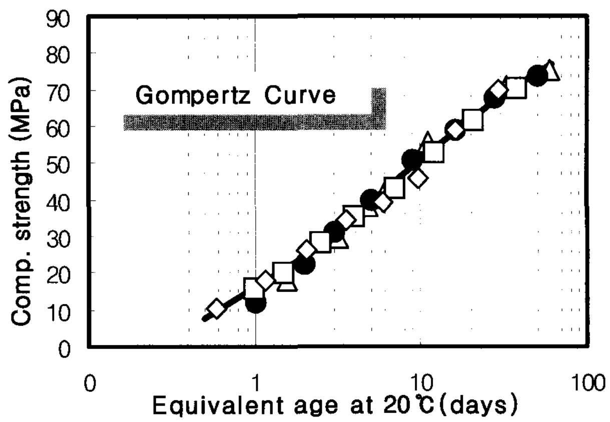
(b) Maturity function (W/B-35 %)

Fig. 4 Compressive strength of high-strength concrete according to equivalent age

Fig. 4(a) and (b) represented by age conversion factor show the correlation of maturity with the strength of high-strength concrete according to curing temperature. It indicates that Freiesleben function based on the Arrhenius equation accounts for the influence of temperature better than the Rastrup function. Therefore, it is recommended to use activation energy value by Freiesleben function in the strength prediction of high-strength concrete.



(a) W/B-30 %



(b) W/B-35 %

Fig. 5 Relation between high-strength concrete and equivalent age according to Gompertz equation

Table 5 The constant calculated by strength prediction model

Gompertz equation : $Fc = F_\infty \exp\{-a(1/M)^b\}$							
W/B-30 %				W/B-35 %			
F_∞	a	b	R^2	F_∞	a	b	R^2
1165.05	1.6587	0.3907	0.978	1152.65	2.0546	0.4094	0.993

4.3 Strength prediction of high-strength concrete

Table 5 presents the results of strength prediction according to Gompertz equation.[15] Fig. 5(a) and (b) shows the relations of predictive strength by prediction formula and strength measured actually. It indicates that Gompertz curve has highest coefficient of determinence value in every age through the experiments. Therefore, it can be recommended to use Gompertz curve for strength prediction of high strength concrete.

5. Conclusions

The final results through this study on the correlation between the compressive strength of high-strength concrete and maturity are as follows:

(1) Freiesleben function based on the Arrhenius equation accounts for the influence of temperature better than the Rastrup function. Therefore, Freiesleben function can be recommended for the strength prediction of high-strength concrete exactly.

(2) Gompertz curve showed highest coefficient of determinence value, it can be recommended as a good method to predict the exact strength.

The experimental study proves that the strength prediction of high-strength concrete by the equivalent age can be regarded as comparatively significant and efficient for a good grasp of the strength prediction.

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