論 文

[1165] PREDICTION OF STRENGTH DEVELOPMENT OF HIGH STRENGTH CONCRETE BY USING MODIFIED EQUIVALENT AGE METHOD

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1. INTRODUCTION

Several methods for prediction of strength development of concrete have been proposed until now. "Maturity" is one of the familiar method [1], in which hydration of cement or rate strength development is assumed to be described by a linear function of age and temperature. However, because of some deficiency in this method, the "equivalent age" method as an another approach was proposed[2]. In this method, the hydration process of cement is assumed to follow the Arrhenius equation which is described by an exponential form.

The datum temperature and activation energy are the key feature of maturity and equivalent age method, respectively. Until now these two parameters were not so clearly defined. However, the latter approach was best able to account for the combined effect of time-temperature on strength gain[3].

In the case of high strength concrete, there is not so many publication in the region of the rate of strength development. This paper represents the results of rate strength development of the four series of low water-cement ratios:(0.28, 0.32, 0.37 and 0.45). In this experiment the specimens were cast and cured under constant curing temperatures: 5, 10, 20, 30 and 40℃ until testing age.

An exponential equation based upon the modified equivalent age is proposed. Analysis of the data shows more acceptable fitting than two above mentioned methods.

2. EXPERIMENTAL PROGRAM

In this experiment Ordinary Portland Cement was used. The coarse and fine aggregate were crushed stone (maximum size 20 mm) and river sand respectively. Type of admixture was SP-9HS. The mixture proportions and the characteristics of the fresh concrete are given in tables (1 and 2). The specimens were cast and cured under predetermined constant curing temperatures: 5, 10, 20, 30 and 40℃. The total number of the specimens were 580, which were cast in cylindrical molds (100mmφ by 200mm).

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Table 1-The Mix proportion of the Concrete

W/C %	Cement	Water	Coarse Agg.	Fine Agg.	Add.(%of Cement)
			kg/m3		
28	607(192)	170	683(253)	964(365)	2.2
32	531(168)	170	745(276)	967(366)	1.8
37	459(145)	170	791(293)	983(372)	1.5
45	378(145)	170	875(324)	967(366)	1.5

The number in paranthesis are volume of the materials(1/m3)

3. DATA ANALYSIS AND RATE DEVELOPMENT OF THE CONCRETE

The relationship representing the variation of the rate development with temperature is the key aspect of a suitable maturity function for prediction of strength development. In this regard, by using the present data suitability of the maturity and Arrhenius functions in representing this relationship are examined.

Maturity function- The linear relationship is as follows

$$K(T)=k1(T-T1) \quad \text{----------(1)}$$

where

K(T)=rate development,day^{-1}

T =curing temperature °C

T1 =datum temperature °C

K1 =constant

Arrhenius function- The rate development is as follows

$$K(T)=k2 \exp.(-E/RT) \quad \text{----(2)}$$

Where

K2=constant,day^{-1}

E =activation energy,J/mole

R =gas constant= 8.3144 J/K-mole

T =absolute curing temp.,Kelvin

To examine the coordination of these two function and the data , the datum temperature and the E/R value are calculated [4]. As an example, figure 1 shows the reciprocal of the strength which is plotted versus the reciprocal of age when water-cement ratio is 0.28. However, K(T) for every concrete mixtures are calculated as follows

$$K(T)=\frac{1/Su}{(1/S)/(1/age)} \quad \text{---(3)}$$

Table 2-Properties of the Fresh Concrete

W/C (%)	Tem. °C	U.W t/m³	Flow cm	Slump cm	Air %
28	5	2.43	21	4	2.0
	10	2.43	28	21.0	2.0
	20	2.45	51	23.0	1.6
	30	2.45	22	15.0	1.5
	40	2.47	25	18.0	1.9
32	5	2.4	23	9.0	2.6
	10	2.4	26	18.0	2.7
	20	2.43	39	22.0	2.3
	30	2.44	23	15.5	1.6
	40	2.44	28	21.0	2.0
37	5	2.39	26	18.5	2.7
	10	2.4	26	18.5	2.5
	20	2.41	36	21.0	1.7
	30	2.43	29	19.5	1.3
	40	2.42	26	18.0	2.2
45	5	2.38	29	18.5	2.5
	10	2.38	36	21.5	2.5
	20	2.4	34	20.0	2.2
	30	2.41	28	17.0	1.8
	40	2.41	24	13.0	2.3

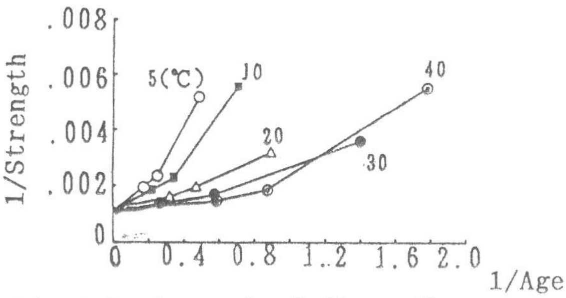

Fig.1-Reciprocal of Strength Versus Reciprocal of Age

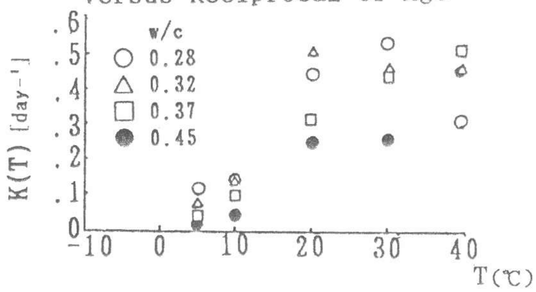

Fig.2-K(T) Versus Curing Temperature

where
$1/S_u$ is the intercept and $(1/S)/(1/age)$ is slope of the best fitting line. Figure.2 shows the variation of the K(T) versus temperature. Eq.2 can be expressed as a linear equation by using natural logarithm.

$$\ln K(T) = \ln K2 - (E/R)(1/T) \quad (4)$$

Figure 3 shows ln K(T) which is plotted versus reciprocal absolute temperature. The feature of figures (2 and 3) show that :

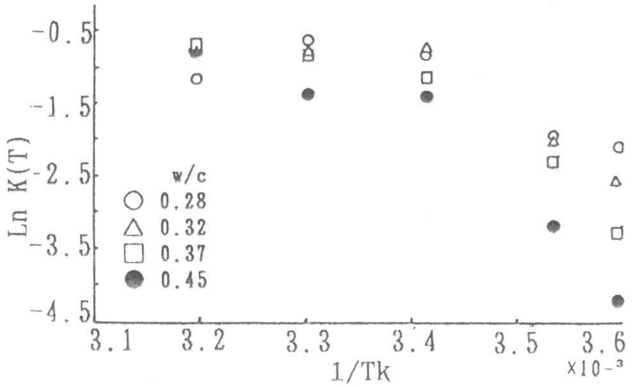

Fig.3-Ln K(T) versus Reciprocal of Absolute Temperature

1-The rate development (K(T)) depends on of W/C ratio,

2-Over the curing temperature range that was studied, the linear function did not provide an accurate representation of the temperature dependence of strength development.

However as an another result over the range of 5℃ to 20℃ curing temperature, a linear relationship between rate development and curing temperature can be concluded. In this regard, fig.4 shows the compressive strength of the concrete mixtures which are plotted versus equivalent age. The constants B and E/R are calculated by linear regression analysis. The E/R values are given in the figure. The line in the figure 4 declares that an exponential equation is the best fitting curve for the concrete specimens as follow

$$S = S_u . \exp\{-(D/t_e)\} \quad (5)$$

where
S =strength at the te , Kgf/cm2
Su=strength at infinite age , Kgf/cm2
D =constant, days.
te=equivalent age with 20℃ reference temperature.

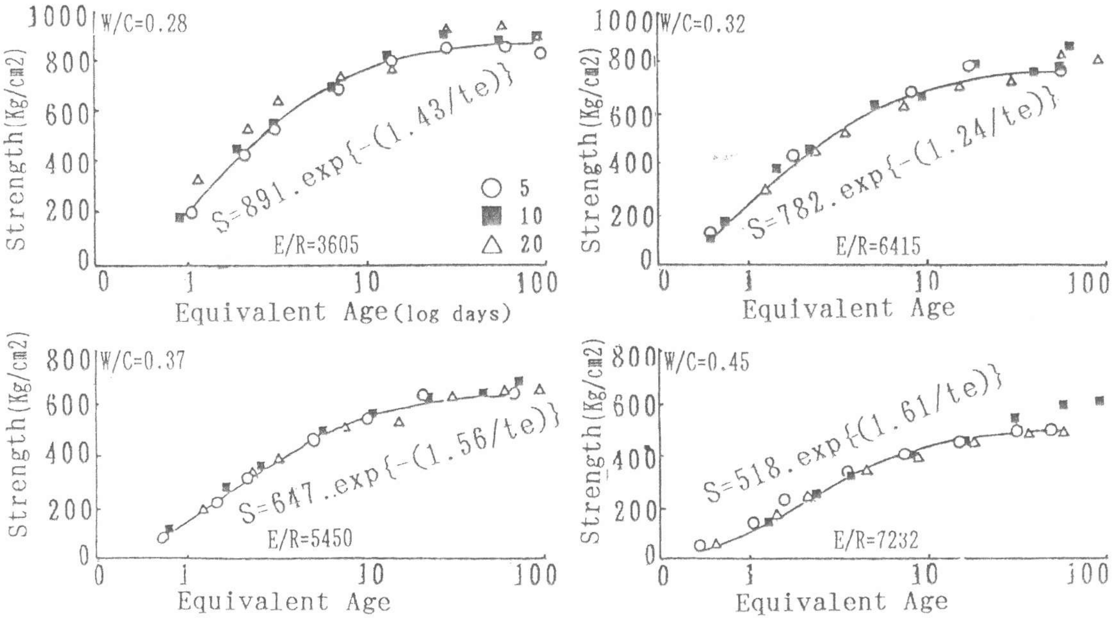

Fig.4-Compressive Strength Versus Equivalent Age at 20(℃)

4.A PROPOSAL FOR STRENGTH DEVELOPMENT BY MODIFIED EQUIVALENT AGE METHOD.

Referring to figure 1, it is assumed that an exponential equation can cover all the data more accurately than a linear equation. This equation can be expressed as follow

$$1/S=1/Su.\exp(B/t) \text{--------------} (6)$$

where:

S = the strength at the age t and

Su= the strength at infinite age.

B = constant, day

Table 3 shows the value of the parameters in the exponential equation in the concrete mixtures. These parameters are computed by regression method. For simplicity, Eq.(6) can be changed to :

$$S=Su.\exp(-B/t) \text{-----------------} (7)$$

It is clear that constant B depends on two factors

1-Final strength (Su); and

2-Curing temperature (t).

Furthermore, B value can be defined as the age of concrete in which, 37 percent of final strength can be obtained as follow

if B=t then S=0.37 Su.

For evaluating B, figures 5 shows the relation between B and Su. It seems that the B value varies in acordance with water-cement ratio, but its variation for curing temperature above 20 is not so considerable. However, a linear relationship between B and Su exists as in figure 5. On the other hand, the effect of curing temperature on B value also is given in the figure 6. This figure shows that the relationship between B and curing temperature can be expressed by a power equation.

By nonlinear regression method, the combined effect of curing temperature and final strength on B value is evaluated as follow

$$B = \alpha T^{\beta} + \gamma Su + C \text{----------} (7\text{-}1)$$

Meanwhile, the effect of curing temperature on Su is expressed as follow

$$1/Su=E(T)+F \text{---------------} (7\text{-}2)$$

The constant values of the above equations are shown in Table 4.

Table 3-Parameters and Corrolation-Coe. of The Exponential Eq.

W/C %	Tem. °C	A 1/(kg/cm²)	B days	C.coe.
28	5	0.00117	2.8834	0.98
	10	0.001106	2.2777	0.975
	20	0.001115	1.11784	0.988
	30	0.00107	0.84037	0.98
	40	0.000996	0.932288	0.94
32	5	0.0013	3.607	0.98
	10	0.00128	2.345	0.98
	20	0.00132	1.092	0.99
	30	0.00127	0.9568	0.99
	40	0.001208	0.8637	0.96
37	5	0.001548	4.216	0.96
	10	0.00154	2.752	0.98
	20	0.00163	1.2658	0.99
	30	0.00158	0.979	0.99
	40	0.00161	0.8248	0.96
45	5	0.002	4.76	0.96
	10	0.00213	3.179	0.97
	20	0.00182	1.477	0.99
	30	0.0019	1.244	0.99
	40	0.0021	0.901	0.97

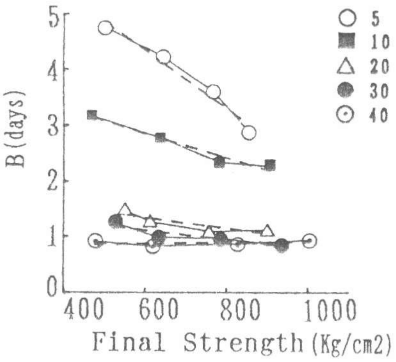

Fig.5-B Value Versus Final Strength

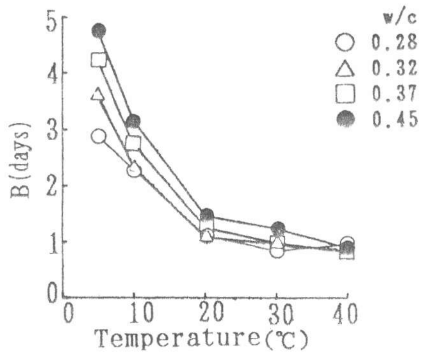

Fig.6-B Value Versus Curing Temp.

Table 4-The Constant Values of Equations(7-1, 7-2)

W/C	α	β	γ	C	E	F
0.28	15.40	-0.1329	6.84xE-3	-15.35	-4.20xE-6	0.00118
0.32	10.62	-0.4184	7.42xE-3	-7.52	-2.22xE-6	0.00132
0.37	12.35	-0.646	0.0111	-7.32	+1.79xE-6	0.00154
0.45	13.29	-0.466	-4.15xE-3	+0.56	--------	--------

Considering the exponential equation of strength development and using the concept of "equivalent age", which represents the age at a reference curing temperature that would result in the same strength gain as under the actual temperature, the following relation can be obtained

$1/S(t)=1/S(20)$ --------------------------(8) and then

$At.\exp(Bt/dt)=A20.\exp.(B20/d20)$ --------(9)

$At/A20=\exp.(B20/d20-Bt/dt)$ -------------(10)

by taking natural logarithm

$\ln(At/A20)=(B20/d20-Bt/dt)$ -------------(11)

using a transform value for age of the concrete as follow

$E20=1/d20$ and $Et=1/dt$ -----------------(12)

$E20=1/B20(\ln At/Bt+Bt.Et)$ --------------(13)

the "modified equivalent age" is defined as follow

$tme=1/E20$ -------------------------------(14)

Fig.(7) shows compressive strength of the concrete mixtures which is plotted versus "modified equivalent age". The best fit exponential equation

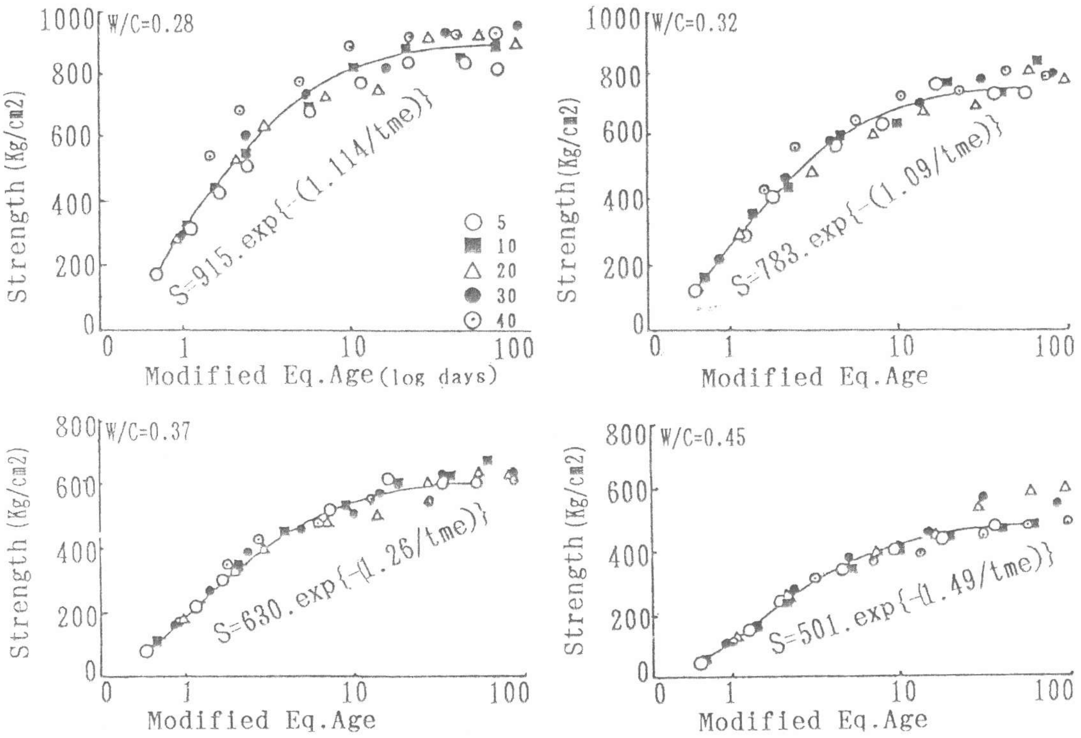

Fig.7-Compressive Strength Versus Modified Eqivalent Age

for the concrete are given in the figure. It is be noted that because of complexity effect of early curing temperature on infinite strength of concrete ,the effect of this parameter on B value is not so clear.

Consequently, figure 8 shows a comparison of estimated strengths plotted versus measured strengths. The best fitting is observed in the early age strength. On the other hand; although scatter exist in the later stage, but almost the estimated strengths in the later age are below the measured strength.

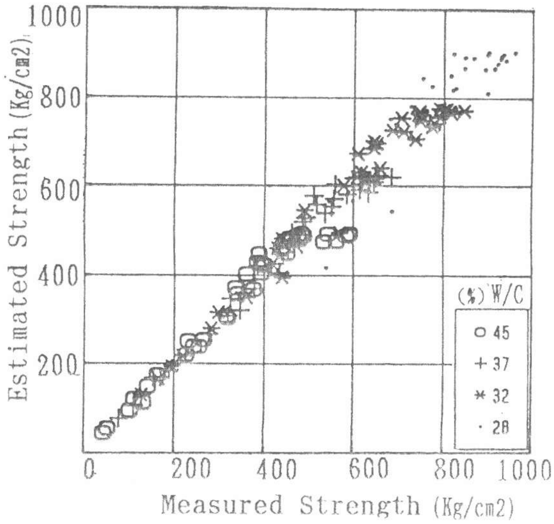

Fig.8-Relation between Calculated and Measured Values

CONCLUSION.

This study as a result of a series of experiments on low water-cement ratio shows that:

1) There is not a quite linear relationship between strength rate development and temperature-time factor over the range of 5℃ to 40℃.

2) Therefore in this range applying of a linear simple relation of $M=\Sigma(T-T_o)dt$ as a criterion for strength development is not valid.

3) By data analyzing as described in sec. (3), the activation energy value can be obtained. It is be noted that, only over the range of 5℃ to 20 C a unique relationship between strength and equivalent age exist. However, this will be valuable,in particular, in cold weather concreting.

4) Because curing temperature affects the final strength of concrete, it is impossible to find a unique strength versus the maturity functions. However, a new method based on exponential equation for the rate development is proposed. By this method a relationship between strength and "modified equivalent age" independent of curing temperature is obtained. It is be noted that, in this regard further research is needed.

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