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PREDICTING THE EARLY STRENGTH DEVELOPMENT CHARACTERISTICS OF PRECAST CONCRETE PRODUCTS

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ABSTRACT

Precast concrete products are usually manufactured through steam curing to increase productivity in plants. However, few studies have comprehensively investigated the effect of steam curing on the early strength development of concrete products. This study focused on the manufacturing pattern involving two steam-curing cycles per day, where strength development characteristics crucially affect the strength and quality of the stripped products. The effects of steam-curing temperature and mix constituents on early strength development characteristics were examined using two equivalent age equations: maturity rule and Arrhenius law; characteristics obtained using the Arrhenius Law were found to be more accurate.

Keywords: precast concrete products, equivalent age, compressive strength, arrhenius law, maturity rule.

INTRODUCTION

During manufacturing, cracks may occasionally occur in precast concrete products, mostly immediately or a few minutes after stripping. This phenomenon may be caused by a sudden difference in temperature between the core and the surface of the product after stripping, which can be generated because of either accelerated curing using high-temperature steam or early stripping. This temperature gradient induces excessive tensile stress at the surface [1], which may in turn lead to noticeable cracking, particularly in winter. In room temperature-cured concrete, this cracking phenomenon can be predicted to a certain degree through thermal analysis or thermal stress analysis by using such software as the Mass Concrete Program of the Japan Concrete Institute. However, the early strength development characteristics of steam-cured concrete differ substantially from those of room-temperature-cured concrete [2-4], which makes commercial software-based thermal analysis less accurate.

In Japan, the decreasing birthrate and aging population is contributing to a shortage of workers in the construction industry. Moreover, areas around concrete and concrete-product plants are witnessing increasing urbanization. These two trends are spurring the use of high-fluidity concrete, which requires less compaction. Ground granulated blast-furnace slag is often used as an admixture in high-fluidity mixes; this ameliorates the environmental impact of construction activities by reducing CO_2 emissions and salt damage to offshore structures. Understanding the strength development characteristics of steam-cured concrete, especially in the early stage is essential not only for analysing thermal stresses and predicting cracking but also for improving the production efficiency and quality of precast concrete products; however, few studies have investigated these characteristics.

Therefore, this study investigated the early strength development characteristics of steam-cured concrete by examining the effects of curing temperature and the presence of admixture on the early compressive strength of precast concrete products.

MATERIALS AND METHODS

Materials and mixtures

Table-1 lists the materials used in the experiments, and Table-2 lists the mixtures. Two types of mixtures with a fixed water-binder ratio (W/P = 31.9%) were used: Mixture H in which no admixture was added and Mixture B in which the admixture was replaced 20wt% of the cement.

Table-1. Materials used in the experiments.

Material	Code	Type	Specific gravity
Cement	C	High-early-strength Portland cement	3.14
Admixture	Sg	Ground granulated blast-furnace slag Specific surface area: 4000 cm^2/g	2.92
Fine aggregate	S	Land sand Absorption = 1.18	2.60
Coarse aggregate	G	Crushed stone 2005 Absorption = 0.92	2.66
Superplasticizer	SP	High-range water-reducing agent (Type I)	1.02

Table-2. Experimental mixtures.

Mixture	W/P (%)	S/A (%)	Unit Weight (kg/m^3)						
			W	C	Sg	S	G	SP	W
H	31.9	41.0	134	420	0	765	1126	5.46	134
B			134	336	84	762	1122	5.46	134

Curing temperature

Figure-1 illustrates the curing curves for H-40 and H-50. This study focused on the manufacturing pattern involving 2 steam-curing cycles per day, which is typically used to accelerate the curing of precast concrete products; the strength development characteristics crucially affect the strength and quality of the stripped products. Therefore, the target manufacturing cycle period was 6-7 h, from mixing to stripping, which was realized by setting the pre-curing period to 1 h and the retention period at maximum temperature to 4 h. The temperature of the mixed concrete was set at 20 °C, and the maximum temperature was set at 40 °C and 50 °C. Assuming some probable worst cases, scenarios in which the temperature increased and then decreased were not considered in this study.

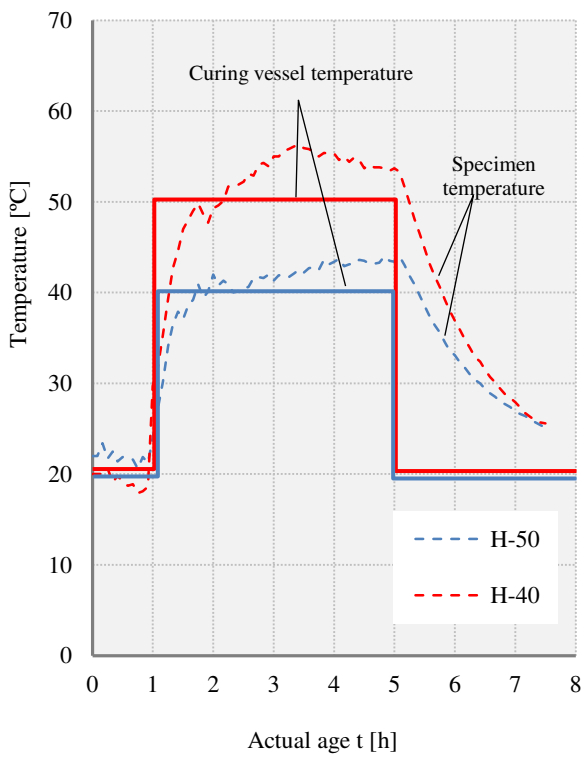

Figure-1. Steam-curing temperature and specimen temperature.

Experiment combinations

Table-3 lists the four experiment combinations: Mixture H and Mixture B were both investigated at maximum temperatures of 40 °C and 50 °C. Thus, the effects of both curing temperature and the admixture on the early compressive strength of precast concrete products were examined.

Table-3. Combination of the experiments.

Symbol	Mixture	Max temp.
[Mix-Max temp.]	[binder type]	[ºC]
H-40	Cement only	40
H-50		50
B-40	replaced by slag	40
B-50		50

Measures

The compressive strength and temperature history of 100 mm × 200 mm cylindrical specimens were the test measures. Measurements were performed at concrete ages of 4.5, 5, 5.5, 6, 6.5, 7 and 8 h. Temperature history was recorded using a thermocouple embedded in the core of the specimens.

METHODS OF PREDICTING STRENGTH DEVELOPMENT

Equivalent age

The equivalent age method is effective for evaluating the mechanical characteristics of concrete having an unsteady temperature history. Generally, it means a material age where the effect of curing temperature on the hydration reaction is converted to be equivalent to the degree of hydration at a curing temperature of 20 °C.

In this study, previously proposed equations of equivalent age (te) namely the maturity rule and Arrhenius law, were used to evaluate the effect of steam-curing temperature.

Maturity rule

The maturity rule (Equation. (1)) is based on rules of thumb for estimating the strength of concrete depending on the curing temperature and period [5, 6]:

$$t_e = \int_0^t \frac{(T_k + 10)}{30} dt \tag{1}$$

where Tk is the environmental temperature in degrees celsius. It is widely used because of its ease of application.

Arrhenius law

Equation. (2) presents the Arrhenius law-based equivalent age equation. Activation energy (U_h) has been calculated using various equations [7, 8]. In this study, the rules of thumb–based equation proposed by [9] (Equation. (3)) was used.

$$t_e = \int_0^t \exp\left[\frac{U_h}{R}\left(\frac{1}{293} - \frac{1}{T_k}\right)\right] dt \tag{2}$$

$$\frac{U_h}{R} = 4600\left[\frac{30}{T_k - 263}\right]^{0.39} \tag{3}$$

Where Uh is the activation energy (J/mol) and R is the gas constant (J/mol•K).

RESULTS AND DISCUSSIONS

Compressive strength

Figure-2 is a plot of compressive strength as a function of actual age. Regression (Equation. 4) was performed on the test data presented in the figure. A logarithmic curve was used to express the relationship between early strength and equivalent age, as validated previously [10].

$$\sigma_c = a \cdot \log_e(t_e) + b \tag{4}$$

whereσ_c is the compressive strength of concrete (N/mm^2) and t_e is the equivalent age (h).

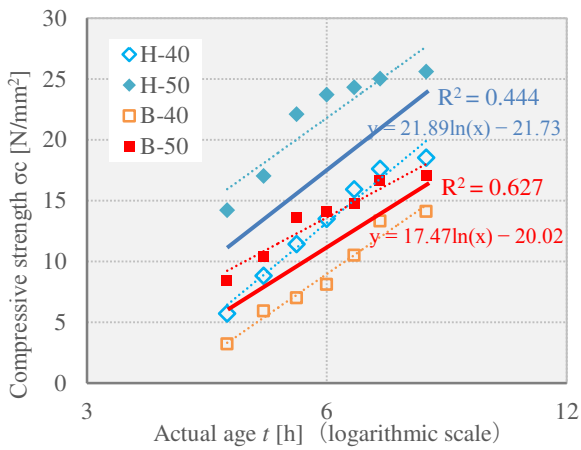

Figure-2. Relationship between compressive strength and actual age.

As evident from Figure-2, irrespective of the mixture, the higher the steam-curing temperature, the higher the compressive strength. In addition, for Mixture B which contains slag, the increase in strength with increasing steam-curing temperature was lower than that for Mixture H which does not contain any slag. This behaviour is attributable to the low early strength of granulated blast-furnace slag. Therefore, the early strength of concrete decreases with increasing slag: cement ratio [11, 12].

Equivalent age calculations

Maturity rule

Figure-3 illustrates the relationship between compressive strength and equivalent age obtained using the maturity rule equation. The two types of mixtures exhibited different strength development trends. At a given equivalent age, Mixture B yielded the same compressive strength at different steam-curing temperatures. By contrast, in Mixture H, compressive

strength varied with curing temperature. Therefore, the maturity rule is not applicable to mixtures that do not contain slag.

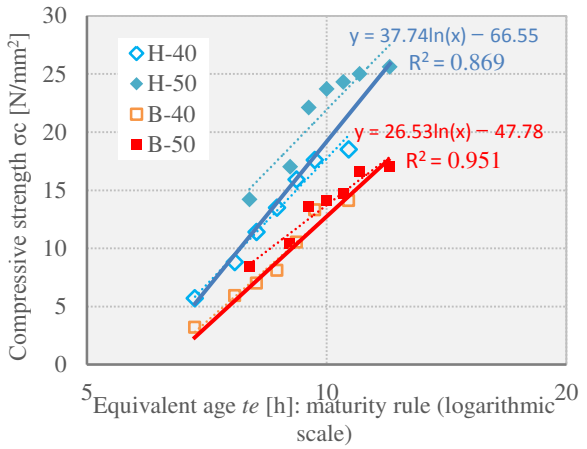

Figure-3. Relationship between compressive strength and equivalent age (maturity rule).

Arrhenius law

Figure-4 shows the relationship between compressive strength and equivalent age according to the Arrhenius law-based equation. In contrast to the curves obtained using the maturity rule, no steam curing temperature-dependent variation was observed in the compressive strength of the two mixtures. Therefore, the Arrhenius law–based equation is applicable to steam-cured concrete, which is typically subjected to high temperatures immediately after pouring.

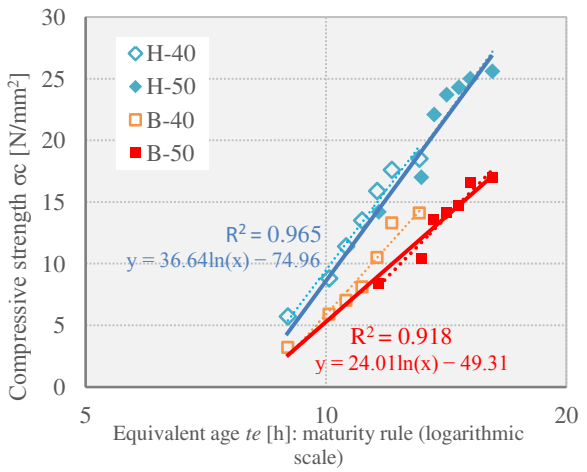

Figure-4. Relationship between compressive strength and equivalent age (Arrhenius law).

Correlation evaluation

Figures 2-4 present the regression curves and the coefficients of multiple determinations (R^2) irrespective of curing temperature, and Figure-5 presents the corresponding correlation coefficients (R). The correlation coefficient calculated using the maturity rule is low for the mixture with no added slag, and the correlation coefficient calculated using the Arrhenius lawis slightly lowerfor the mixture with added slag. Nevertheless, the correlation coefficient is high when using the equation proposed by [9] and when using the Arrhenius law-based equation for all mixtures. In other words, the Arrhenius law-based equation can more accurately express the effect of steam-curing temperature on the early strength development of concrete.

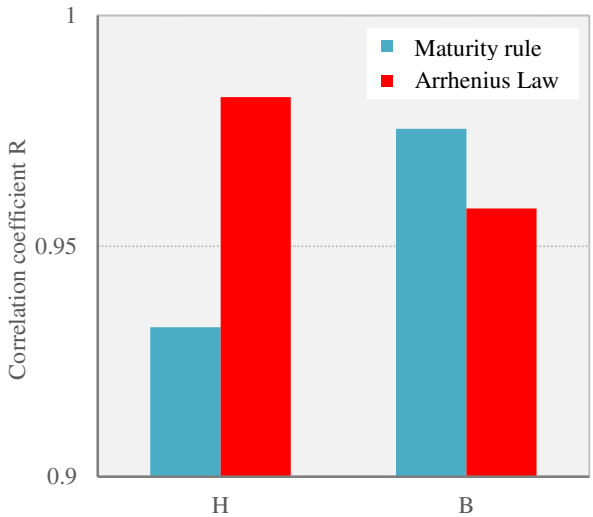

Figure-5. Correlation coefficients.

Most studies on strength estimation using the maturity rule and the Arrhenius law have mainly focused on materials with medium to long material age[5,6,13], whereas few studies have addressed the estimation of compressive strength of materials subjected to early high temperatures or early stripping, such as precast concrete products subjected to steam curing. Therefore, the strength estimation inconsistencies observed in this study at high curing temperatures will be investigated in the future.

CONCLUSIONS

In this study, the effect of steam-curing temperature and mix constituents on the early compressive strength was examined and the applicability of two age-strength equations was experimentally studied. The following conclusions were drawn:

(1) The effects of the added ground granulated blast-furnace slag on the strength development characteristics of specimens subjected to different temperature histories were stronger in the mixture with no admixture than in those with admixture.

(2) For a given mixture, the equivalent age equation incorporating the Arrhenius law and the rules of thumb proposed by [9] for expressing the relationship between curing temperature and strength of concrete is more accurate than is the equation based on the maturity rule.

REFERENCES

[1] Takayoshi M., Hideaki K., Junya F. and Shigeyuki D. 2015. Effect of expansive admixture on early stripped concrete products (in Japanese).In: 70th JSCE Annual Meeting, Japan Society of Civil Engineers. pp. 349-350.

[2] Y. Shoji, H. Takeshita and H. Sawara. 1994. Effects of steam curing on properties of hardened super flowing concrete (in Japanese). Concrete Research and Technology of the Japan Concrete Institute. 16(1).

[3] K. Mayuyama, K. Uji, A. Ueno and K. Ono. 2011. Study on the strength properties and pore structures of concrete products under different steam curing conditions (in Japanese). Concrete Research and Technology of the Japan Concrete Institute. 33(2).

[4] Kenzo S., Tsuyoshi K. and Tetsuo H. 2011. Effect of steam curing conditions and binder types on mechanical characteristics of steam-cured concrete (in Japanese). In: Annual Conference of the Seibu Branch of Japan Society of Civil Engineers. 31.

[5] N. Ito, H. Mihashi and K. Kirikoshi. 2004. Apparent activation energy and equivalent age of concrete influenced by curing temperature history (in Japanese). Concrete Research and Technology of the Japan Concrete Institute. 15(1).

[6] Keishiro I., Takafumi N., Tatsuya H. and Hidetaka U. 1999. Study on effects of creep for tensile cracking in early aged concrete (in Japanese). In: Proceedings of the Japan Concrete Institute. pp. 201-213.

[7] N. Ito, H. Mihashi and K. Kirikoshi. 2004. Apparent activation energy and equivalent age of concrete influenced by curing temperature history (in Japanese). Concrete Research and Technology of the Japan Concrete Institute. 15(1).

[8] M. Taniguchi, O. Katsura, T. Sagawa and Y. Hama. 2011. Effects of the mineral composition of cement on the temperature dependency of strength development (in Japanese). Journal of Structural and Construction Engineering, Architectural Institute of Japan. 76(661): 443-448.

[9] A. Saetta, B. Schrefler and R. V. Vitaliani. 1993. The carbonation of concrete and the mechanism of moisture, heat and carbon dioxide flow through porous materials. Cement and Concrete Research. 23(4): 761-772.

[10] T. Kikuchi, I. Katayama, S. Taki and Y. Kuroda. 2013. Estimation based on rules of thumb of early strength development of concrete used in precast concrete members in site (in Japanese). Concrete Research and Technology of the Japan Concrete Institute. 35(1).

[11] N. Ozeki, T. Idemitsu, T. Yamasaki and S. Ishimastu. 2000. Study on mixture proportion and several physical properties of high fine grinding ground granulated blast-furnace slag (in Japanese). Concrete Research and Technology of the Japan Concrete Institute. 22(2).

[12] Hiroyoshi K., Akinori N., Hiroyuki D. and Toyoaki M. 2001. Strength development and autogenous shrinkage of high-flow concrete with limestone powder (in Japanese). Journal of the Society of Materials Science. 50(5): 543-549.

[13] Koji K. and Tetsuya I. 2015. Compressive strength development properties of low water-binder ratio mortar and application of temperature-time function (in Japanese). In: 70th JSCE Annual Meeting, Japan Society of Civil Engineers. 471.