PREDICTING THE EARLY STRENGTH DEVELOPMENT CHARACTERISTICS OF PRECAST CONCRETE PRODUCTS

Takayoshi Maruyama¹, Nozomi Nakajima², Shinichiro Hashimoto³ and Shigeyuki Date⁴
¹Research Division, Technical Department, Tsurumi Concrete Kabushiki Kaisha, Japan
²Course of Architecture/Building and Civil Engineering, Graduate School of Engineering, Tokai University, Japan
³Department of Civil Engineering, Faculty of Engineering, Fukuoka University, Japan
⁴Department of Civil Engineering, School of Engineering, Tokai University, Japan
E-Mail: sdat@tokai-u.jp

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 CO₂ 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.

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

Table-2. Experimental mixtures.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>W/P (%)</th>
<th>S/A (%)</th>
<th>Unit Weight (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W</td>
<td>C</td>
<td>Sg</td>
</tr>
<tr>
<td>H</td>
<td>31.9</td>
<td>420</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>134</td>
<td>336</td>
<td>84</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Mixture</th>
<th>Max temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Mix-Max temp.]</td>
<td>[binder type]</td>
<td>ºC</td>
</tr>
<tr>
<td>H-40</td>
<td>Cement only</td>
<td>40</td>
</tr>
<tr>
<td>H-50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>B-40</td>
<td>replaced by slag</td>
<td>40</td>
</tr>
<tr>
<td>B-50</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

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 ºC.

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]:

\[ t_e = \int_0^{(T_k + 10)/30} dt \]  

(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 (Uh) has been calculated using various equations [7, 8]. In this study, the rules of thumb–based equation proposed by [9] (Equation. (3)) was used.

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

(2)

where \( U_h \) 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].

\[ \sigma_c = a \cdot \log_e(t_e) + b \]  

(4)

where \( \sigma_c \) is the compressive strength of concrete (N/mm²) and \( t_e \) is the equivalent age (h).

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

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.

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. 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.

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


