Early Age Deformation, its Resultant Stress and Creep Properties of Concrete with and without Internal Curing Subjected to High Temperature History at an Early Age

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Introduction

JCI Guidelines for Control of Cracking of Mass Concrete 2016
(JCI Guidelines)

Main Target: newly placed members such as wall-type structures restrained predominantly EXTERNALLY by existing members

\[ E_e(t_e) = \Phi(t_e) \times E_c(t_e) \]
\[ \Phi = 0.65 \]
\[ \Phi = 0.42 \]

Schematic diagram of stress in concrete
A surface layer of newly placed members such as cap beams supported by piles is predominantly internally restrained due to nonlinear distribution of temperature in sections.

In this case, tensile stress develops up to a time at the peak temperature and thereafter compressive stress develops.
Introduction-Objective

**Objective**

to investigate creep behavior of concrete, in which tensile stress develops up to a time at the peak temperature and thereafter the tensile stress decreases, by measuring concrete deformation, rebar strain in a reinforced concrete prism subjected to high temperature history with a maximum of 70°C at an early age.

**JCI Guidelines**

Cracks due to internal restraint are not addressed in the verification because the cracks can be prevented in construction stages by using appropriate curing methods.

HOWEVER, structures could not always be cured sufficiently due to requirement of shorter construction period and so on. In that case, it is important to verify the superficial cracks beforehand.
Experimental Programs
Materials and Mix proportions

<table>
<thead>
<tr>
<th>Name</th>
<th>BB</th>
<th>BB-PCFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>s/a</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>W</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>C</td>
<td>413</td>
<td>413</td>
</tr>
<tr>
<td>S</td>
<td>766</td>
<td>651</td>
</tr>
<tr>
<td>PCFA</td>
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<td>100</td>
</tr>
<tr>
<td>G</td>
<td>952</td>
<td>952</td>
</tr>
</tbody>
</table>

Unit content (kg/m³)

Slump
Target: 12±2.5 (cm) 13.5 10.0

Air content
Target: 4.5±1.0 (%) 4.0 4.5

C(cement): Portland blast furnace slag cement-type B

Porous ceramic fine aggregate derived from roof tile waste
Item of Investigation

- **Mechanical properties**
  - Compressive strength and modulus of elasticity under compression
  - at the age of 1, 3, 7, 28 and 91 days
  - with a diameter of 100 mm and a height of 200 mm

- **Length change of concrete under temperature change**
  - with an embedded gauge including thermocouple
  - at the center of a prism with a size of 100x100x400mm

- **Elastic strain in reinforcement induced by shrinkage and temperature change**
**Item of Investigation**

- **Elastic strain in reinforcement induced by shrinkage and temperature change**

- A D19-bar located at the center of the cross section of prismatic specimen
- Two self-temperature-compensation gauges

- Strain of each gage in bare rebar was measured in a temperature-controlled room ranging from 10°C to 70°C automatically and repeatedly until relationship between temperature rise and the measured strain overlapped that between temperature drop and the measured strain.

- Elastic strain in reinforcement was obtained by subtracting the strain in bare rebar from measured strain in reinforced concrete prism.
Curing Conditions

The top surface of all specimens were sealed after casting
> Stored in a temperature-controlled room
> High temperature history with the maximum temperature of 70°C
> Remolded at the age of 7 days, and sealed, and then stored at 20°C

Temperature inside of both concrete specimens were almost the same as that in the temperature-controlled room.
Results and Discussion
Compressive Strength and Modulus of Elasticity

Temperature-adjusted concrete age, \( t_e \)

\[
t_e = \sum_{j=1}^{n} \Delta t_i \cdot \exp \left[ 13.65 - \frac{4000}{273 + T(\Delta t_i)/T_0} \right]
\]

where, \( \Delta t_i \) is the period of constant temperature continuing in concrete (day); \( T(\Delta t_i) \) is concrete temperature for \( \Delta t_i \) (°C); \( T_0 \) is 1°C.

Compressive strength strength, \( f'_c(t_e) \)

\[
f'_c(t_e) = \frac{t_e - S_f}{a + b(t_e - S_f)} f'_c(t_n)
\]

where, \( t_n \) is the strength control age of concrete cured under water at 20°C (day); \( a \) and \( b \) are experimental constants; \( S_f \) is the temperature adjusted concrete age corresponding to initiation of hardening (day); \( f'_c(t_n) \) is the compressive strength of concrete at \( t_n \) (N/mm²).

Modulus of elasticity, \( E_c(t_e) \)

\[
E_c(t_e) = C_3 \times f'_c(t_e)^{C_4}
\]

where, \( C_3 \) and \( C_4 \) are constants.
Compressive Strength and Modulus of Elasticity

\[ f'_c(t_e) = \frac{t_e - S_f}{a + b(t_e - S_f)} f'_c(t_n) \]

\[ E_c(t_e) = C_3 \times f'_c(t_e)^{C_4} \]

\( f'_c \) and \( E_c \) with BB-PCFA were almost the same as those of BB. They were higher during ages of 1 day to 10 days, and lower after the age of 10 days compared with those recommended by the JCI Guidelines.
Free Strain in Concrete, $\varepsilon_{as}+\varepsilon_{\Delta T}$

$\varepsilon_{as}+\varepsilon_{\Delta T}$ increased and decreased corresponding to the temperature rise and drop up to the age of 7 days.

Temperature in specimen

$\varepsilon_{sh}+\varepsilon_{\Delta T}$ in BB-PCFA

$\varepsilon_{as}+\varepsilon_{\Delta T}$ in BB

Assumed $\varepsilon_{as}$ in BB-PCFA (TEC10.4)

Assumed $\varepsilon_{as}$ in BB (TEC11.4)

Assumed $\varepsilon_{as}$ in JCI guidelines

Thermal expansion coefficient (TEC) was assumed to be a constant of BB: $11.4 \times 10^{-6}/^\circ$C

BB-PCFA: $10.9 \times 10^{-6}/^\circ$C measured with the cylindrical specimen after shrinkage was negligible.
Shrinkage and Temperature Change-Induced Strain in Reinforcement, $\varepsilon_{s,e}$

The elastic strain $\varepsilon_{s,e}$ in reinforcement increased with the temperature rise and decreased with the temperature drop, regardless of mix proportion. After reaching a constant temperature, the strain increased monotonically with time.

The change in $\varepsilon_{s,e}$ with age during temperature rise and drop obtained from BB-PCFA is slightly larger than that from BB.

> This difference in the change could be explained by the difference in TEC between both concrete samples. That is, the TEC gap between BB-PCFA and reinforcement can be larger than that between reinforcement and BB.
Effective Modulus of Elasticity $E_e$

Strain in concrete and reinforcement can be expressed as follows.

$$\varepsilon_c = \varepsilon_{c,e} + \varepsilon_{cr} + \varepsilon_{sh} + \varepsilon_{c,\Delta T} \quad \varepsilon_s = \varepsilon_{s,e} + \varepsilon_{s,\Delta T}$$

Based on the compatibility of real strain $\varepsilon_c = \varepsilon_s$, stress related strain $(\varepsilon_c + \varepsilon_{cr})$ in concrete can be obtained as follows.

$$\varepsilon_{c,e} + \varepsilon_{cr} = \varepsilon_{s,e} + \varepsilon_{s,\Delta T} - (\varepsilon_{as} + \varepsilon_{c,\Delta T}) = \varepsilon_{s,e} + \alpha_s \Delta T - (\varepsilon_{as} + \varepsilon_{c,\Delta T})$$

Stress in concrete can be given by the following equation using $E_e$.

$$\sigma_c = E_e (\varepsilon_c - \varepsilon_{as} - \varepsilon_{c,\Delta T}) = E_e (\varepsilon_{c,e} + \varepsilon_{cr})$$

Stress in concrete can be obtained by measuring elastic strain in reinforcement.

$$\sigma_c = -\frac{A_s}{A_c} \sigma_s = -pE_s \varepsilon_{s,e}$$

$E_e$ can be evaluated as follows.

$$E_e = \frac{\sigma_c}{\varepsilon_{c,e} + \varepsilon_{cr}} = \frac{-pE_s \varepsilon_{s,e}}{\varepsilon_{c,e} + \varepsilon_{cr}}$$
Stress and Stress related strain in concrete with age

The stress related strain in BB increased at a higher rate than that of BB-PCFA in temperature rise, whereas the BB decreased in roughly parallel with the BB-PCFA in temperature drop.

The stress related strain in BB increased at a higher rate than that of BB-PCFA in temperature rise, whereas the BB decreased in roughly parallel with the BB-PCFA in temperature drop.

\[ \varepsilon_{c,e} + \varepsilon_{cr} = \varepsilon_{s,e} + \varepsilon_{s,\Delta T} - (\varepsilon_{sh} + \varepsilon_{c,\Delta T}) \]

Tensile stresses in both concretes were generated during temp. rise, decreased during temp. fall, and increased after reaching a constant temperature of 20°C.

Stress related strain in BB increased at a higher rate than that of BB-PCFA in temperature rise, whereas the BB decreased in roughly parallel with the BB-PCFA in temperature drop.
Relationship between stress related strain and stress in concrete

\[
(1) \ y = 0.0071x + 0.129 \\
R^2 = 0.974
\]

\[
(2) \ y = 0.0208x - 0.629 \\
R^2 = 0.708
\]

\[
(3) \ y = 0.0106x + 0.331 \\
R^2 = 0.945
\]

\[
(4) \ y = 0.0235x - 0.331 \\
R^2 = 0.970
\]

\[
(1) \ 0.55-1.4 \text{days} \\
(2) \ 1.4-1.54 \text{days} \\
(3) \ 1.54-7.0 \text{days} \\
(4) \ 7.0-200 \text{days}
\]

(1) from initiation of hardening to the age at \( T_{\text{max}} \)
(2) from the age at \( T_{\text{max}} \) to the age at \( T_{\text{max}} +1 \text{day} \)
in temperature adjusted age
(3) from the age of at \( T_{\text{max}} +1 \text{day} \) in temperature adjusted age
to the age of 7 days
(4) from the age of 7 days to the age of around 200 days

\[
E_e = \frac{\sigma_c}{\varepsilon_{c,e} + \varepsilon_{cr}}
\]

\[
\Phi = \frac{E_e}{E_c}
\]
Effective modulus of elasticity and reduction coefficient

(1) Temp. rise: $E_e$ as well as $\Phi$ of both concrete in this study < those in JCI guidelines

(3) Temp. fall:
- BB: $E_e$ as well as $\Phi$ in this study < those in JCI guidelines
- BB-PCFA: $E_e$ as well as $\Phi$ in this study slightly < those in JCI guidelines

(4) 20°C constant after high temperature history:
$E_e$ as well as $\Phi$ of both concrete in this study ≈ those in JCI guidelines
Evaluation of Creep Coefficient

Stress related strain can be expressed as follows by using the expression of $E_e$.

$$E_e = \frac{\sigma_c}{\varepsilon_{c.e} + \varepsilon_{cr}} = \frac{-pE_s\varepsilon_{s.e}}{\varepsilon_{c.e} + \varepsilon_{cr}} \Leftrightarrow \varepsilon_{c.e} + \varepsilon_{cr} = \frac{-pE_s\varepsilon_{s.e}}{E_e} = -n_e p \varepsilon_{s.e}$$

where, $n_e$ is ratio of modulus of elasticity of reinforcement ($E_s$) to $E_e$ of concrete.

The ratio $n_e$ can be described the following equation from $\varepsilon_{c.e} + \varepsilon_{cr} = \varepsilon_{s.e} + \varepsilon_{s,\Delta T} - (\varepsilon_{as} + \varepsilon_{c,\Delta T})$

$$-n_e p \varepsilon_{s.e} = \varepsilon_{s.e} + \varepsilon_{s,\Delta T} - (\varepsilon_{as} + \varepsilon_{c,\Delta T}) \Leftrightarrow n_e = \frac{1}{p} \left\{ -1 + \frac{\varepsilon_{as} + \varepsilon_{c,\Delta T} - \varepsilon_{s,\Delta T}}{\varepsilon_{s.e}} \right\}$$

Based on $n_e = \frac{E_s}{E_c}(1 + \chi \varphi) = n(1 + \chi \varphi)$, creep coefficient ($\varphi$) can be obtained.

$$\varphi = \frac{1}{\chi} \left\{ -1 + \frac{n_e}{n} \right\} = \frac{1}{\chi} \left\{ -1 + \frac{1}{np} \left( -1 + \frac{\varepsilon_{as} + \varepsilon_{c,\Delta T} - \varepsilon_{s,\Delta T}}{\varepsilon_{s.e}} \right) \right\}$$

where, $\chi$ is aging coefficient; $n$ is ratio of $E_s$ to $E_c$.

Increment of creep coefficient at the step of $j$ can be expressed as follows.

$$\Delta \varphi_j = \frac{1}{\chi} \left\{ -1 + \frac{1}{n_j p} \left( -1 + \frac{\Delta \varepsilon_{as,j} + \Delta \varepsilon_{c,\Delta T,j} - \Delta \varepsilon_{s,\Delta T,j}}{\Delta \varepsilon_{s.e,j}} \right) \right\}$$
### Evaluation of creep coefficient

<table>
<thead>
<tr>
<th>BB</th>
<th>Temp. rise</th>
<th>Temp. fall</th>
<th>20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>Period</td>
<td>0.55-1.4days</td>
<td>1.4-1.54days</td>
<td>1.54-7days</td>
</tr>
<tr>
<td>Ratio of modulus of elasticity $n_j = \frac{E_s}{E_c,avg,j}$</td>
<td>12.3</td>
<td>6.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Aging coefficient $\chi$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Δfree strain in concrete $\Delta e_{sh,j} + \Delta e_{c,AT,j}$</td>
<td>127</td>
<td>-8</td>
<td>-375</td>
</tr>
<tr>
<td>Δthermal strain in RB $\Delta e_{x,AT,j}$</td>
<td>329</td>
<td>-6</td>
<td>-494</td>
</tr>
<tr>
<td>Δelastic strain in RB $\Delta e_{x,e,j}$</td>
<td>-104</td>
<td>-4</td>
<td>72</td>
</tr>
<tr>
<td>Creep coefficient $\chi \phi$</td>
<td>1.6</td>
<td>-3.4</td>
<td>2.9</td>
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<tr>
<td>$\phi$</td>
<td>2.0</td>
<td>-4.2</td>
<td>3.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BB-PCFA</th>
<th>Temp. rise</th>
<th>Temp. fall</th>
<th>20°C</th>
</tr>
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<tr>
<td>Step</td>
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<td>Aging coefficient $\chi$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Δfree strain in concrete $\Delta e_{sh,j} + \Delta e_{c,AT,j}$</td>
<td>169</td>
<td>-8</td>
<td>-351</td>
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<tr>
<td>Δthermal strain in RB $\Delta e_{x,AT,j}$</td>
<td>342</td>
<td>-5</td>
<td>-490</td>
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<tr>
<td>Δelastic strain in RB $\Delta e_{x,e,j}$</td>
<td>-105</td>
<td>-4</td>
<td>106</td>
</tr>
<tr>
<td>Creep coefficient $\chi \phi$</td>
<td>0.8</td>
<td>-2.3</td>
<td>0.8</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1.0</td>
<td>-2.9</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Assuming $\chi$ of 0.8 constant,

The evaluated creep coefficients of BB-PCFA were around 1.0 during temperature rise and fall, and those of BB were 2.0 and 3.7 for the same periods, respectively. PCFA may decrease the effect of creep due to its internal curing effect.

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Conclusion
The present study investigated the creep properties of sealed concrete restrained with steel bar subjected to temperature variation assuming that in mass concrete, which were made of blast furnace slag cement Type B with and without internal curing agent PCFA (BB-PCFA and BB). The following main conclusions are drawn within the limit of the study.

The effective modulus of elasticity considering creep effect ($E_e$) during temperature rise, which was obtained from regression line for measurements, was significantly smaller than that recommended by the 2016 Guidelines for each of the above mentioned both concretes. The $E_e$ during temperature drop of BB was also significantly smaller than that by the guideline, and however, that of BB-PCFA was slightly smaller than that by the guideline.

The creep coefficients of BB was remarkably larger than those of BB-PCFA during both temperature rise and drop corresponding to $E_e$, which may be due to the effect of internal curing with PCFA.

Further experiments are needed to improve the reliability of the present data.

Thank you for your kind attention.