Temperature Dependency of Autogenous Shrinkage of Ultra High-strength Concrete

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ABSTRACT: In this contribution, temperature dependency of autogenous shrinkage of ultra high-strength concrete whose binder is premixed silica fume cement with W/B=0.15 is investigated. Experimental factors are temperature of fresh concrete and elevated temperature history that are emulating difference of temperature history due to placing season. As a result, following conclusions are obtained 1) autogenous shrinkage of ultra high-strength concrete has two stages from the point of view of a rate of shrinkage, i.e., earlier age (stage1) and later age (stage2), 2) lower temperature of fresh state increase autogenous shrinkage at stage1, 3) higher temperature develop larger autogenous shrinkage, especially over 40°C at stage2.

1 INTRODUCTION

A sensitivity of ultra high-strength concrete (UHSC) to cracking is mainly determined during the hardening process. In order to evaluate durability of UHSC, it is important to grasp volume changes (thermal dilation and autogenous shrinkage) of UHSC in early age.

The placing season makes a big difference on temperature of concrete. A gap of maximum temperature of UHSC between summer and winter or may reaches more than 20°C.

However, the relationship between temperature and autogenous shrinkage has not obtained quantitatively yet. To clarify temperature dependency is hoped on the practical using of UHSC.

Experimental result that many cracks in a full-scale reinforced UHSC column placed in winter were observed rather than that placed in summer is reported by the authors (Maruyama et al. 2007). That paper indicated that one of the causes of this phenomenon was temperature dependency of autogenous shrinkage. Namely, lower temperature of fresh state increased the autogenous shrinkage.

In this contribution, temperature dependency of autogenous shrinkage of cement paste and mortar, whose binder was low heat Portland cement with 10%-replaced silica fume, was investigated. Experimental factors were temperature of fresh state (10°C, 20°C, 30°C) and temperature history (constant temperature and elevated temperature history +25°C, and +45°C).

Table 1 Materials

<table>
<thead>
<tr>
<th>Materials Type</th>
<th>Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low heat Portland cement</td>
<td>Density: 3.22 g/cm³, Specific surface area: 3600 cm²/g</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Density: 2.24 g/cm³, Specific surface area: 17.1 m²/g</td>
</tr>
<tr>
<td>Crushed sand</td>
<td>Surface dry density: 2.57 g/cm³, Water absorption: 2.62 %, S</td>
</tr>
<tr>
<td>Crushed stone</td>
<td>Surface dry density: 2.95 g/cm³, Water absorption: 0.48 %, G</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>Polycarboxylic acid type, SP</td>
</tr>
<tr>
<td>Anti-forming agent</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 2 Mixture Proportions

<table>
<thead>
<tr>
<th>Mix</th>
<th>Cement type</th>
<th>(W+D+SP)/C*</th>
<th>Unit content (kg/m³)</th>
<th>SP/C*</th>
<th>D/C*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W</td>
<td>C*</td>
<td>S</td>
<td>G (%)</td>
<td>(%)</td>
</tr>
<tr>
<td>SFLC-P</td>
<td>SFLC</td>
<td>0.15</td>
<td>316</td>
<td>2108</td>
<td>0</td>
</tr>
<tr>
<td>SFLC-C</td>
<td>SFLC</td>
<td>0.15</td>
<td>161</td>
<td>1074</td>
<td>456</td>
</tr>
</tbody>
</table>

C*: Silica fume-premix cement

In the case of that temperature changes are given, it is impossible to measure only autogenous shrinkage without thermal dilation. Therefore, thermal expansion coefficient (TEC) of cement paste and mortar was measured simultaneously with total strain to subtract thermal dilation from total strain.
2 EXPERIMENTAL PROCEDURES

2.1 Materials and Mixture Proportions

Table 1 lists the materials used for this experiment. The types of fine aggregate and coarse aggregate are that used for general UHSC. In this study, coarse aggregate is comminuted with a maximum size of 5mm, because specimen size is fixed as 10x60x370 mm to avoid distribution of temperature in specimen.

The mix composition of the experiment is shown in Table 2. Water-to-binder ratio is fixed with 0.15 in both cement paste and mortar.

2.2 Experimental equipment for measurement of autogenous shrinkage

Fig 1 shows detail of experimental equipment for measurement of autogenous shrinkage and TEC. Laser displacement meter, whose accuracy is 0.5 μm is used for measuring displacements in each end of specimen. The copper mould, whose surface is sufficiently flat and smooth, was used. Furthermore, specimen was covered by polyester film in order to avoid water evaporation and eliminate the restrain by the mould. The copper mould is insulated on the outside covering with polystyrene, whose thickness is 30mm.

The temperature control of the specimen is provided by the temperature controlled water in copper mould. Thermo-couples measure the temperature in the center and end of the specimen. The difference of temperature in each thermo-couples was less than 0.2°C and the average-value of each thermo-couples was adopted by temperature of specimen.

2.3 Temperature history

Two types of temperature histories were applied for the specimens.

Temperature history of specimen is composed of two kinds of parameters, i.e. temperature of fresh state and maximum elevated temperature.

The temperature of fresh state is 10, 20, and 30°C, and maximum elevated temperature from fresh state, which is emulating temperature history of full scale RC member, is +0°C, +25°C, +45°C.

One is “Base temperature history” that is composed combinations of temperature of fresh state (10°C, 20°C, 30°C) and elevated temperature history (+0°C, +25°C, +45°C), which is emulating temperature history of full scale RC member. Experimental results of the temperature of fresh state are different from assumed temperature and maximum difference is 9°C, however all specimens reached assumed temperature within 40min.

In this contribution, specimen condition is described as [P or C] (cement paste or mortar) [assumed temperature of fresh state] - [assumed maximum temperature].

The other temperature changes is “Temperature pulse”, that was applied at specified age to grasp a time-dependent change of TEC. Specified ages were 5, 10, 16, 21, 26, 31, 38, 53, 68, 88, 125, 131hour for elevated temperature conditions and every 4 hours for isothermal conditions (See Fig.3). Velocity of temperature changes was 0.2°C/min.

2.4 The estimation of thermal expansion coefficient

TEC was obtained with linear regression from the amount of temperature changes and total strain changes. “Temperature pulse” has 4steps of temperature changes (Step1: +5°C, Step2: -5°C, Step3: -5°C, Step4: +5°C) and above estimation are conducted each steps.
Now, Fig.2 shows relationships between temperature and total strain in the range of one “Temperature pulse”. In early age, autogenous shrinkage develops rapidly. Thus it is difficult to measure only thermal dilation without influence of autogenous shrinkage (See Fig.2 (a)). Therefore, when calculating TEC, an influence of autogenous shrinkage to total strain had to be removed. In this study, autogenous shrinkage is supposed that it develops lineally during 2steps-50min (up phase and down phase, e.g., Step1 and Step2). Estimated TEC value of those steps are taken average, so as to cancel influence of autogenous shrinkage.

2.5 Experimental procedure of Equilibrium Relative Humidity

Cement paste and mortar are provided to some plastic receptacles (10x60x90mm), and sealed with aluminum adhesive tape. These samples were given “Base temperature history”, and taken out from temperature control chamber at specified age (12h,18h, 24h,30h,36h,3d,7d). After that air-cooled samples to normal temperature comminuted under 20mm. Crushed samples were put into aluminum bag. The air in this bag was stirred and let it 30min to make equilibrium conditions. After that, the equilibrium relative humidity in aluminum bag was measured at 20°C. The accuracy of relative humidity sensor was ±3% in the range of 50~95% and that of temperature sensor is ±0.5°C.

3 RESULTS AND DISCUSSION

3.1 Thermal expansion coefficient

Fig.3 middle figures show time-dependent change of TEC. In all conditions, a reduction of TEC is observed before 16h. This experimental result was already reported by some papers. (e.g. Loukili et al.2000) This is due to the dominance of water, whose TEC is approximately $70\times 10^{-6}$ (/°C) declining as specimen is hardening. After that, there is an increase. TEC of specimens who are given elevated temperature history shows peak at the time those temperatures reach maximum, and the TEC value is higher as the elevated temperature is larger.

As Mayer has pointed out, TEC have a dependency of relative humidity and there is a peak at about 70%RH (1950). So, it could be considered one of a
cause of this phenomenon is relative humidity dependency of TEC.

Fig.3 bottom show time-dependent change of equilibrium relative humidity, and Fig.4 shows relationships between equilibrium relative humidity and TEC. It is confirmed that TEC has increased with a reduction of equilibrium relative humidity, which is caused by self-desiccation. While, when comparing specimens who have the same value of relative humidity, there is a difference of TEC value. Thus, there may be other factors of determining TEC value, in addition to relative humidity.

Those phenomena are observed both cement paste and mortar, however the value changes of mortar are smaller than cement paste. This is mainly because TEC of aggregate are much lower than cement paste. In this study, we represent those phenomena as under equation Eq. (1), Eq. (2) (See Fig.3) to calculate thermal dilations.

\[
\alpha(t) = a \cdot \exp(b \cdot t) + c \cdot \ln(t) + d \quad (1)
\]

\[
\alpha(t) = e \cdot \ln(t - f) + g \cdot t + h \quad (2)
\]

where \( \alpha(t) \) is TEC \((\times 10^{-6}/\degree C)\), \( t \) is age (h), \( t_0 \) is the age that Eq.(1) switch over Eq.(2) (h), and \( a-h \) are constants (See Table.4). Eq.(1) and Eq.(2) can be applied at \( 0 < t < 170 \).

### 3.2 Autogenous shrinkage

When calculating stress in RC member, there is a datum point (e.g. the age when stress was induced). In that case, Eq. (3) is used for calculating dilation.

\[
\varepsilon_{\text{aut}}(t) = \varepsilon_{\text{total}}(t) - \varepsilon_{\text{thermal}}(t)
\]

\[
= \varepsilon_{\text{total}}(t) - \alpha(t) \cdot \{ T(t) - T_d \} 
\]

where \( \varepsilon_{\text{aut}}(t) \) is calculated autogenous shrinkage \((\times 10^{-6})\), \( \varepsilon_{\text{total}}(t) \) is total strain \((\times 10^{-6})\), \( \varepsilon_{\text{thermal}}(t) \) is thermal dilation \((\times 10^{-6})\), \( T(t) \) is temperature \((\degree C)\) and \( T_d \) is a datum temperature \((\degree C)\).

If the TEC is constant, autogenous shrinkage also can be calculated with Eq. (3).

However, time-dependent change of TEC was experimentally observed as Fig.3. It might be improper to use Eq. (3) when we discuss about autogenous shrinkage. Practical autogenous shrinkage should be calculated by incremental way, using Eq. (4).
where $\varepsilon_{\text{aut}_n}$ is autogenous shrinkage ($\times 10^{-6}$), $\alpha_n$ is TEC ($\times 10^{-6}/{^\circ}\text{C}$) and $T_n$ is temperature (${^\circ}\text{C}$) at the $n$ time step. We adopted the age when total strain started to decline is $n=0$.

Fig. 5 shows comparing autogenous shrinkage calculated with Eq. (3) and Eq. (4) it was confirmed that thermal dilation in Eq. (3) shows “0 shift”, which caused by temperature changes. This “0 shift” almost take a positive value in early age, and switchover to a negative number with elevating temperature. The maximum difference of autogenous shrinkage calculated with each procedure is $126 \times 10^{-6}$ in positive area and $195 \times 10^{-6}$ in negative area.

Fig. 6 shows the relationship between autogenous shrinkage and concrete adjusted age, according to Eq. (5) (CEB FIP Model Code 90)

$$t_a = \exp \left( \frac{E_a}{RT_a} \left( \frac{1}{T_0} - \frac{1}{T_k} \right) \right) \cdot \Delta t$$

where $t_a$ is temperature adjusted concrete age (h), $E_a$ is activation energy (4000x8.31kJ/mol), $R$ is gas constant (8.31J/(K・mol)), $T_0$ is a datum temperature (293K) and $T_k$ is curing temperature (K)

According to Fig.6, autogenous shrinkage of cement paste was divided into two stages, namely, one is a very early age (Stage.1) from an initial during hardening before about 15h, and the other is after that (Stage.2). The age of boundary between Stage.1 and Stage.2 are determined balance in hardening process, as Takahashi et al. pointed out, Stage.1 is caused by rapidly reduction of porosity and pore size

with chemical shrinkage until a strong solid skeleton is formed (Takahashi et al. 1996).

In Stage.1, specimen who is a low temperature of fresh concrete shows a larger value of autogenous shrinkage. (See Table.5). This tendency is confirmed in other experiment using concrete (Maruyama et al. 2007).

In stage.2, it can be evaluated with above temperature adjusted concrete age until curing temperatures reach 40°C. However, in the range of over 40°C, the velocity of development of autogenous shrinkage become larger.

To evaluate the development of autogenous shrinkage properly in high temperature, it seems that larger activation energy is suitable for autogenous shrinkage behavior of the cement paste with very low water to binder ratio. Fig.7 shows autogenous shrinkage in Stage.2. The horizontal axis is temperature adjusted concrete age whose $E_a$ is $10000x8.31$ in Eq. (5) As is shown in Fig.7, all conditions can be evaluated with same temperature adjusted concrete age.
Temperature Adjusted Concrete Age (h+1)

Autogenous Shrinkage at Stage 2 (×10^-6)

Fig.7  Autogenous Shrinkage at Stage.2 with Cement Paste

The similar trend as that of cement paste was experimentally observed in Mortar. But the concrete age when autogenous shrinkage start to develop of mortar is later than that of cement paste in Stage.1. And unevenness of autogenous value is observed as compared with cement paste. One of the causes of this unevenness is considered that influence of the amount of superplasticizer. Namely, temperature rises were given to mortar specimens with before autogenous shrinkage developed. It is considered that this compulsory temperature changes give any influences to mechanism of autogenous shrinkage.

5) In Stage2, higher temperature develops larger autogenous shrinkage, especially over 40°C, and this phenomenon is not related to temperature of fresh state.

5 ACKNOWLEDGEMENT

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6 REFERENCES

CEB 1990. CEB-FIP MODEL CODE 1990