Control of Concrete Strength during PCCV Construction for Ohi No.3 and No.4 Units

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1. INTRODUCTION

Prestressed concrete containment vessels (PCCV), the second and third in Japan, were adopted for the No.3 and No.4 Units of Ohi Nuclear Power Station. The specified concrete strength was 450 kgf/cm², higher than that for previous PCCV. This is the highest specified concrete strength ever used in nuclear power station construction projects in Japan. The PCCVs were massive concrete structures with internal diameters of 43.0 m, internal heights of 64.5 m, the cylinder wall thickness of 1.3 m and the dome wall thickness of 1.1 m. The main dimension of PCCV was given in Figure-1. Concrete was placed in 14 lifts in the cylinders and 11 lifts in the domes.

Such a massive structure would be subjected to a high temperature hysteresis due to heat of hydration when hardening after placement of concrete during

Fig. 1 Typical Section of PCCV

the initial curing period. With a structure subjected to high temperature, there is a possibility for thermal cracks and, moreover, it is well-known that concrete strength of the structure will not necessarily be equal to that of standard-cured cylinder.

This report describes the method of quality control and results in preventing occurrence of thermal cracks and, moreover, in satisfying the high strength of 450kgf/cm² in the structural concrete by the specified age of 91 days, during the construction of the PCCV's for Ohi No.3 and No.4 Units.

2. Results of Preliminary Studies on Strengths of Structural Concrete

Concrete members 1.3 m in thickness were prepared as models on the actual PCCV walls and the cores taken from the members were tested to investigate the strengths of the structural concrete. The following results were obtained.

1) The strength gain properties in the structural concrete differ depending on the season in which concrete was placed. In the summertime initial strength is high, but there is almost no long-term increase of strength. Conversely, in the wintertime, initial strength is low, but strength increases with age.

2) It will be most reliable for concrete strength of a massive structure to be evaluated by the strength of cylinders cured following the temperature hysteresis to which the structural concrete is subjected, except of cores specimens extracted.

3) Also, it is possible for a relationship to be established between concrete strength of the structure and standard-cured cylinder strength by a multiple regression equation by adding the temperature hysteresis of structure as the explanation variables.

4) Pre-cooling concrete by Liquid-Nitrogen is effective for obtaining the required structural concrete strengths in summer.

3. Field Tests Related to Structural Concrete Strengths

Based on these results, data were accumulated further at the actual construction site during over 1-year period on the strength of cylinders cured to follow the temperature hysteresis of structural concrete (calculated values) and the strength of standard-cured cylinders. Relationships for estimating structural concrete strength for the strength control on the job were obtained from the results, shown in Table-1.

The concrete mix based on this series of investigations is as shown in Table-2.

4. Investigation on Thermal Cracking Prevention Measures

The measures listed in Table-3 were adopted with the purpose mainly of minimizing the temperature rise in the structural concrete after placement. Of these, Measures 1) to 8) had been employed in prevention of thermal cracking in mass concrete in construction of nuclear power plants
Table-1 Estimation Equations for Structural Concrete Strengths

\[ Y_{13} = 0.852 \left[ f_{c13} \right] - 14.5 \left[ T_{m} \right] + 17.2 \left[ T_{r} \right] + 16.3 \pm E [32.6] \]
\[ Y_{13} = 284 \left[ (c/w) \right] - 17.8 \left[ T_{m} \right] + 20.6 \left[ T_{r} \right] - 180.8 \pm E [35.6] \]

\( f_{c13} \): Estimated value for structural concrete strength (13 weeks) (kgf/cm²)
\( c/w \): Standard cured cylinder strength (13 weeks) (kgf/cm²)
\( T_{m} \): Mean temperature of the member (°C)
\( T_{r} \): Monthly average curing temperature of the member (°C)
\( E \): Standard deviation of regression error (kgf/cm²)

Table-2 Concrete Mix (per m³)

<table>
<thead>
<tr>
<th>Fc (kgf/cm²)</th>
<th>Slump (cm)</th>
<th>W/C (%)</th>
<th>S/A (%)</th>
<th>Cement (kg)</th>
<th>Fly ash (kg)</th>
<th>Water (l)</th>
<th>Aggregate (kg)</th>
<th>Admixture (kg)</th>
<th>Plasticiser (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>6-15</td>
<td>38.0</td>
<td>43.7</td>
<td>332</td>
<td>75</td>
<td>159</td>
<td>758</td>
<td>1003</td>
<td>4.45</td>
</tr>
</tbody>
</table>

Table-3 Thermal Cracking Prevention Measures

<table>
<thead>
<tr>
<th>No.</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Use of Moderate Heat Portland Cement</td>
</tr>
<tr>
<td>2</td>
<td>Use of fly ash as additive</td>
</tr>
<tr>
<td>3</td>
<td>Limitation of acceptance temperature for cement (in summer)</td>
</tr>
<tr>
<td>4</td>
<td>Cooling of mixing water (in summer)</td>
</tr>
<tr>
<td>5</td>
<td>Aggregate storage in large corrugated bin with roof</td>
</tr>
<tr>
<td>6</td>
<td>Use of plasticizers</td>
</tr>
<tr>
<td>7</td>
<td>91-day strength control</td>
</tr>
<tr>
<td>8</td>
<td>Planning of placing blocks</td>
</tr>
<tr>
<td>9</td>
<td>Pre-cooling with liquid nitrogen</td>
</tr>
</tbody>
</table>

prior to the introduction of PCCV’s. In adopting Measure 9), the limits of application and the range of the cooling temperature were determined on the basis of preliminary investigations through thermal stress analysis.

The following results were obtained.

1) Cracking is more likely to occur in cylinder pedestal of PCCV’s than in other parts.

2) Concrete is liable to cracking even in parts other than the cylinder pedestals in summer due to the high temperature of concrete during placement.

It has been seen through this investigation that pre-cooling of concrete with liquid nitrogen is effective against these.

5. Pre-cooling of Concrete with Liquid Nitrogen

On the results of these preliminary investigations, precoking of concrete with liquid nitrogen was implemented to prevent thermal cracking and to secure the required structural concrete strengths in summer.

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Fig.-2 Conceptual Drawing of Curing System Following Temperature Hysteresis
Fig. 3 Results of Control of Structural Concrete Strengths

Fig. 4 Relationship between Measured and Estimated Values for Structural Concrete Strengths

The placing concrete temperatures were lowered to 12.5°C and 15.0°C, respectively for No.3 and No.4 units, in the cylinder pedestals of PCCVs, where the likelihood of thermal cracking was the largest. In other parts, too, the placing concrete temperature was lowered to 20°C in summer.

The precooling of concrete was conducted by directly injecting the liquid nitrogen into the truck agitators. For 7 lifts in both Units No.3 and No.4, the concrete volume was 3,814 m³, the total amount of cooling 47,144 m³°C and the amount of liquid nitrogen used 612 tons.

6. Control of Concrete Strength in the Structure

Particular care was taken over the quality control of the concrete strength for the PCCVs as high strength massive concrete with specified concrete strength of 450 kgf/cm² used in the most important structure in the nuclear power plant.
For routine on-site control, strength tests of general-type standard-cured cylinders were performed, and it was ascertained that the strength of structural concrete estimated by the relationships, obtained in the preliminary investigations (Table-1), satisfied the specified concrete strength of 450 kgf/cm².

Parallel to this, the method of confirming the structural concrete strength by the strength of cylinders cured periodically following the temperature hysteresis of structural concrete was also used. Temperature hysteresis curing of structural concrete was of the two kinds of the case of giving the calculated value and the case of directly giving the temperature hysteresis of the actual structural concrete through a system utilizing data communications by personal computer shown in Fig.-2.

The results of the quality control for structural concrete strengths are shown in Figures-3 and 4. It can be seen from Figure-3 that the estimated values for the structural concrete strength and the measured values obtained from the concrete specimen cured in following the temperature hysteresis all satisfy the specified concrete strength of 450 kgf/cm².

Figure-4 shows that the measured values for the structural concrete
stresses are to be found within the 95% reliability range of the estimated values, indicating the high reliability of the equation used.

7. Measured Results for Thermal Stress

Measured results of the temperature and thermal stress in the PCCV cylinder pedestal concrete for Unit No.3 are given in Figures 5 and 6. The analytical values for thermal stress in Figure 6 were obtained by using the analytical values for temperature distribution of PCCV concrete given in Figure 5. Measured and analytical values show very close coincidence for both temperature distribution and thermal stress, and furthermore, the actual thermal stresses generated are smaller than the estimated tensile strengths of concrete resulting in there being no thermal cracking. This was also confirmed through visual inspection.

Investigations were then made on the effects of pre-cooling by means of the same analysis method as that used in Figures 5 and 6. The results, given in Figure 7, indicate that pre-cooling with liquid nitrogen not only lowers the final tensile stress but delays the age at which tensile stresses are generated and is an effective method for prevention of thermal cracking.

8. Conclusion

No harmful thermal cracking was occurred and quality control successfully implemented to obtain the structural concrete strength satisfying the specified strength of 450 kgf/cm² by the specified age during actual construction of PCCV’s.

Reference