ANALYSIS OF THERMAL CRACKS IN CONCRETE GRAVITY DAM SPILLWAY AND CONSTRUCTION CONTROLS

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ABSTRACT

This is a new concrete gravity dam under construction inland in the Chugoku region in Japan, where the minimum winter temperature reaches -6°C. Prior to commencement of construction 3-dimensional temperature stress analysis of the dam body was carried out to identify the parts where there was a risk of thermal cracks, and construction is proceeding while taking measures to reduce the occurrence of cracks. However, during construction, cracks occurred unexpectedly in the spillway at mid elevation, near the position of installation of an orifice pipe of spillway. This paper describes the measures for reduction of cracks based on the initial analysis, the analysis performed after the occurrence of cracks, and the countermeasures taken.

1. INTRODUCTION

1.1 Dam overview

Length of dam crest	:	300 m
Dam height	:	73 m
Dam volume	:	340,000 m^3
Construction period	:	March 25, 2014 to March 31, 2023

Upstream elevation and typical cross-section are as shown in Figures 1-2.

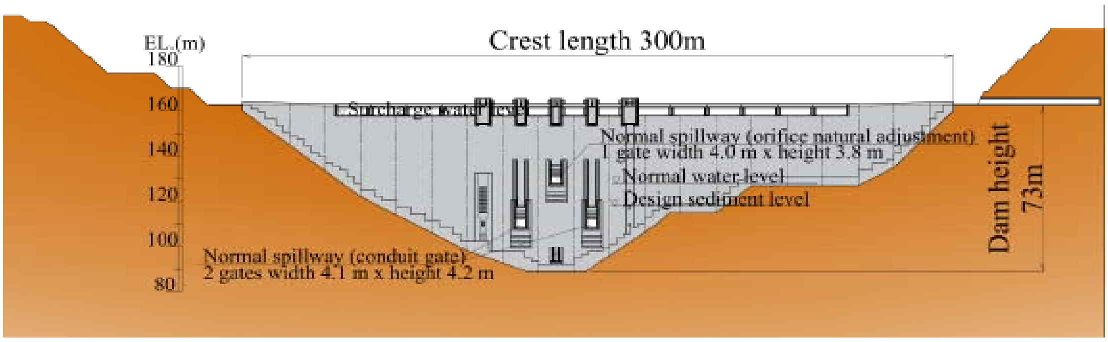

Fig. 1 : Upstream elevation

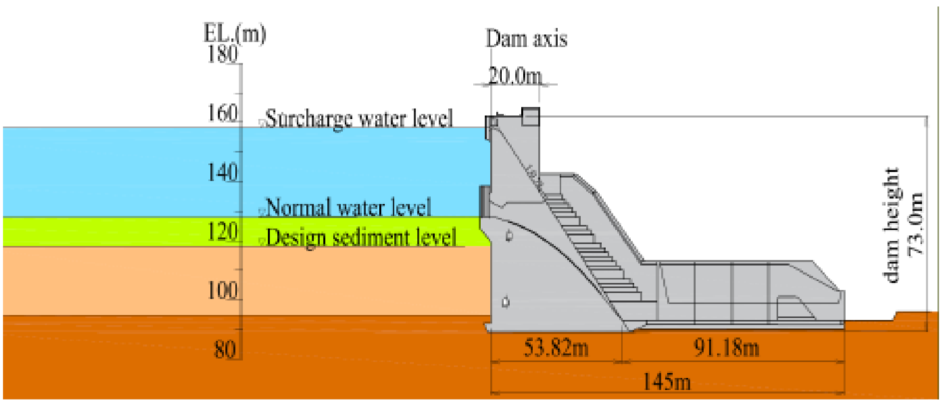

Fig. 2 : Typical cross-section

2. INITIAL ANALYSIS AND MEASURES TO REDUCE CRACKS

2.1 Temperature stress analysis

Three-dimensional Finite Element Method (FEM) temperature stress analysis was carried out on the block of the concrete dam with the largest cross-section, which was considered to have the highest risk of cracks, to assess the risk of the occurrence of thermal cracks. Three-dimensional temperature stress analysis was carried out on each part of the dam body before the start of construction, and measures to reduce the occurrence of cracks were taken so that the probability of occurrence of cracks were 15% or less (crack index 1.40 or higher).

2.1.1 *Analysis conditions*

The input conditions used in the analysis are shown in Table 1.

Table 1: Analysis conditions

Item	Dam body concrete	Foundation rock
Adiabatic temperature rise equation of external concrete (°C)	$Q(t) = 22.3 \times (1 - \exp(-0.405 \times t^{0.655}))$	–
Adiabatic temperature rise equation of internal concrete (°C)	$Q(t) = 18.9 \times (1 - \exp(-0.304 \times t^{0.505}))$	–
Adiabatic temperature rise equation of structural concrete (°C)	$Q(t) = 27.2 \times (1 - \exp(-0.454 \times t^{0.732}))$	–
Heat transfer coefficient (W/m°C)	2.7	3.45
Specific heat (W/m°C)	1.15	0.79
Mass per unit volume (kg/m^3)	2,400	2,650

Also, the boundary condition between the dam body concrete and the external air was input as a heat transfer coefficient.

2.1.2 *Analysis results*

The result of the 3-dimensional temperature stress analysis was a 28% probability of occurrence of cracks (crack index 1.19) without any countermeasures, as shown in Figure 3.

Note that the figure with the analysis results shows the block cut at the center.

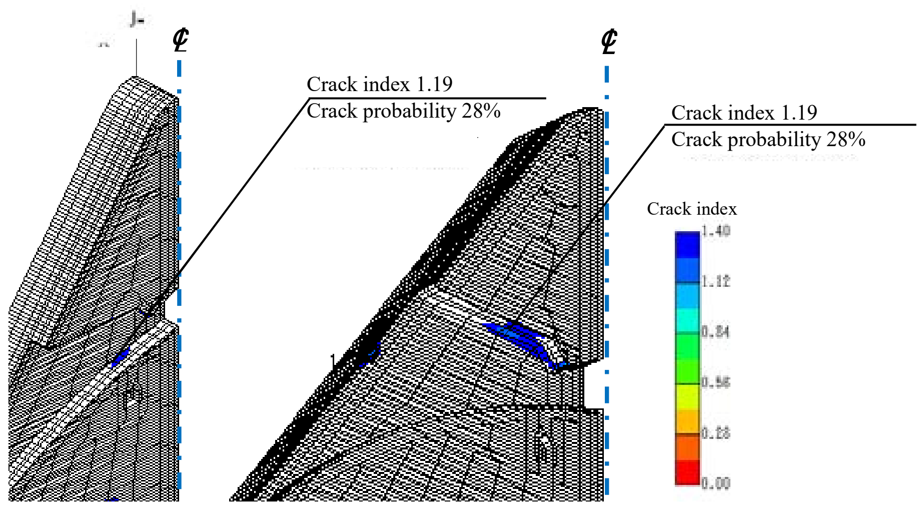

Fig. 3 : Temperature stress analysis results without any countermeasures (distribution of minimum values in the analysis period)

2.1.3 *Countermeasures*

The following measures were taken to reduce the occurrence of cracks so that a 15% probability of occurrence of cracks (crack index 1.40) was satisfied.

2.1.3.1 *Countermeasure 1: Reduce the concrete placement temperature in summer*

By pre-cooling the materials, the concrete temperature in summer was reduced, so that even on days with a maximum air temperature of 35°C the concrete temperature during placement was 21°C. In this way the temperature rise in the interior of the dam body was reduced, reducing the temperature difference with the external air, and reducing the probability of cracks.

The mixed concrete temperature was accurately predicted from heat balance calculations using measurements of the material temperature, and the pre-cooling temperature control was carried out by controlling the cooling temperature of each concrete material. Heat balance calculations are as shown in Table 2. Note that the mixing water was cooled using chillers, the cement was cooled with a cement cooler, and the aggregates were cooled with cold air cooling plant.

Table 2. Heat balance calculation

Concrete Material	Specific heat kJ/kg.K	Mix quantity kg/m³	Unit heat quantity kJ/m³°C	No countermeasure		With countermeasure	
				Material temperature °C	Heat content kJ/m³	Material temperature °C	Heat content kJ/m³
Coarse aggregate (G1) *	0.8	556	444.8	30.0	13,344	14.6	6,494
Coarse aggregate (G2) *	0.8	373.4	298.72	31.0	9,260	15.3	4,570
Coarse aggregate (G3) *	0.8	364.7	291.76	31.7	9,249	16.2	4,727
G1-G3 Surface water	4.19	1.1	4.61	31.5	145	15.8	73
Coarse aggregate (G4) *	0.8	343.7	274.96	32.0	8,799	17.3	4,757
G4 surface water	4.19	3.8	15.92	32.0	509	17.3	275
Fine aggregate (S)	0.8	588.4	470.72	27.5	12,945	27.5	12,945
S surface water	4.19	21.2	88.83	27.5	2,443	27.5	2,443
Cement (C)	1.13	140	158.20	25.9	4,097	25.9	4,097
Mixing water (W)	4.19	61.8	258.94	23.7	6,137	4.0	1,036
Mixer heat**					2,469		2,469
Total			2,307		69,397		43,886
Mixed concrete Temperature				30.1		19.0	

* Coarse aggregate G1~G4 are classified by particle size. G1's size is 150mm~80mm. G2's size is 80mm~40mm. G3's size is 40mm~20mm. G4'size is 20mm~5mm.

$$** \text{ Mixer heat } (\text{kJ}/m^3) = \frac{37.0(kW) * 4(mixers) * \frac{3603(kJ/m^3)}{(kW)} * 0.83(min)}{60(\text{min}) * 3.0(m^3)}$$

2.1.3.2 *Countermeasure 2 : Protection of openings*

Openings such as passages and spillways were covered in winter before the dam body had reached its strength, so that the concrete would not be cooled by cold air entering from the openings.

3. OCCURRENCE OF CRACKS AND INFERENCE OF CAUSES

3.1 Overview of cracks

Cracks occurred near the center of the dam body during construction of the normal spillway block on November 14, 2017. A lift of concrete was placed in this block up to EL 125.0 m on September 30, 2017, then the placement was stopped for installation of the orifice gate for about 1.5 months, after which cracks occurred.

Cracks occurred at 2 locations: near DC+8 m and near DC+21 m. In each case, cracks were parallel to the dam axis direction, and it occurred at about 1/3 and 2/3 of the dam width on the construction joint surface at EL 125.0 m.

Near DC+21 m the maximum width of Crack A was 0.6 mm, and this crack occurred on the EL 125.0 m construction joint surface, virtually perpendicular to the orifice wall surface. On November 14, 2017, there was no crack on the overflow surface, but subsequently on December 5, 2017 Crack A extended to the overflow surface. The crack width at the overflow surface was a maximum of 0.5 mm. Coring was carried out to check the depth of the crack, which showed that the crack had reached a depth of about 3 m.

Crack B near DC+8 m was found on December 7, 2017. On the EL 125.0 m construction joint surface the crack width was a maximum of 0.75 mm, and it extended to a depth of 2 m reaching a passage installed at that position. Crack location diagrams are as shown in Figures 4-5.

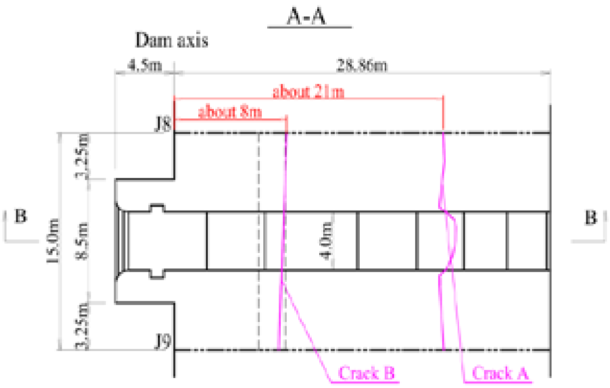

Fig. 4 : Crack location diagram (plan view)

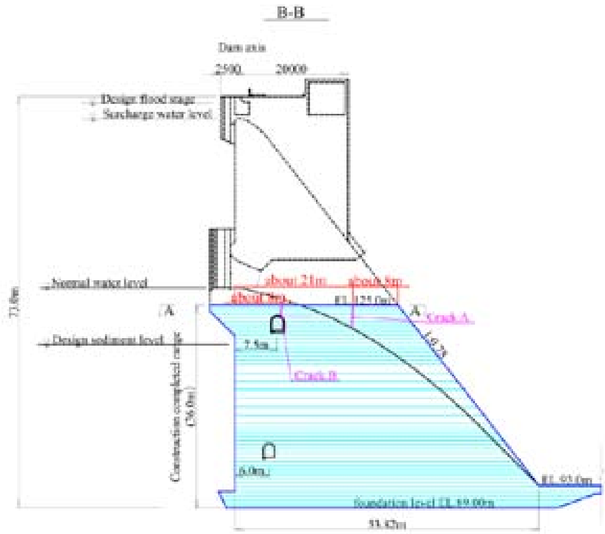

Fig. 5 : Crack location diagram (cross section)

3.2 Inference of causes of cracks

15 year average air temperature and 2017 air temperature at the dam site is as shown Figure 6. These cracks occurred on the surface at which placement had been stopped for 1.5 months, it occurred on November 14, 2017, when there was an unprecedented sudden drop in air temperature, and it extended downwards from the EL 125.0 m construction joint surface. Therefore, it is considered that the cause was thermal cracks due to internal constraint as a result of cooling the construction joint surface for a long period of time. To verify this a temperature stress analysis was performed inputting the actual air temperatures, actual placement temperature, and measured internal temperatures, and the occurrence of cracks was reproduced. Figure 7 shows a comparison of 2016 and 2017 minimum temperatures. In 2016, a low elevation spillway (conduit spillway) had been constructed in an adjacent block, and cracks had been prevented. However, temperature sudden dropped in 2017 compared to 2016 before protection by installing thermal insulation material, and some cracks occurred.

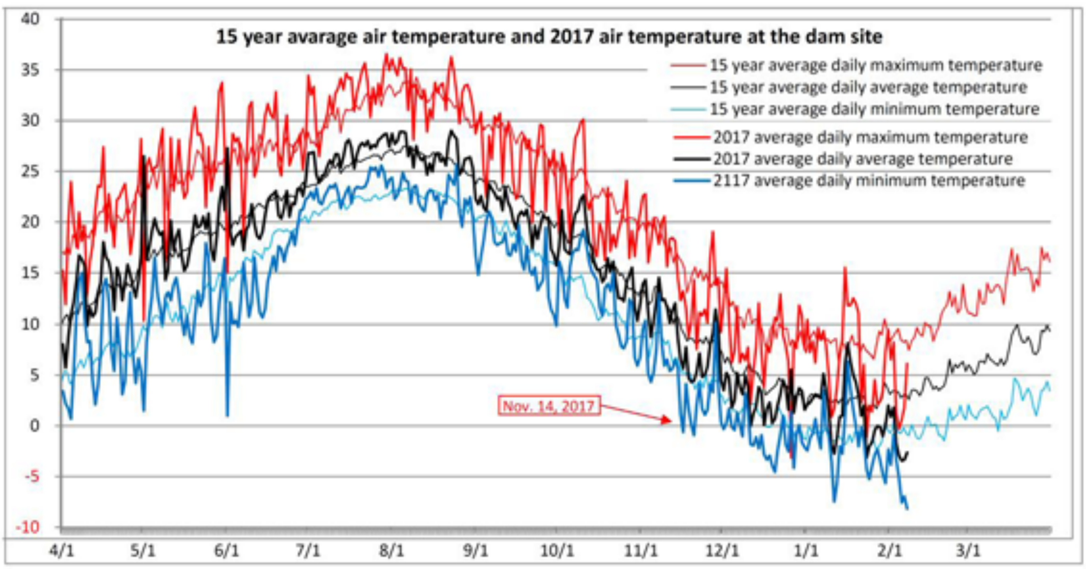

Fig. 6 : Air temperature in 2017 at the dam site

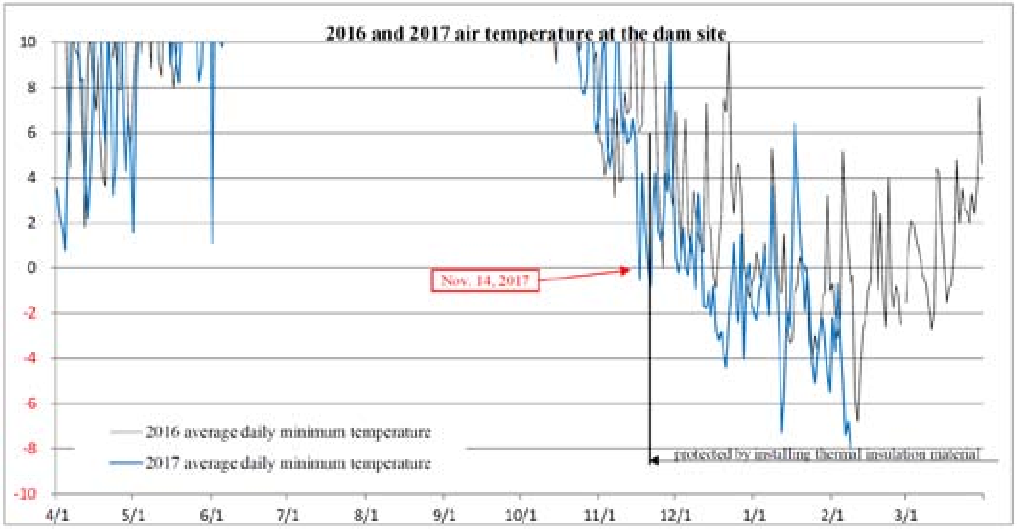

Fig. 7 : Minimum air temperature in 2016 and 2017 at the dam site

3.2.1 *Analysis parameters*

The model from the previous analysis was used, and the measured values of external air temperature, concrete placement temperature, and concrete temperature were used. The measured temperatures used were as shown in Figures 8-9.

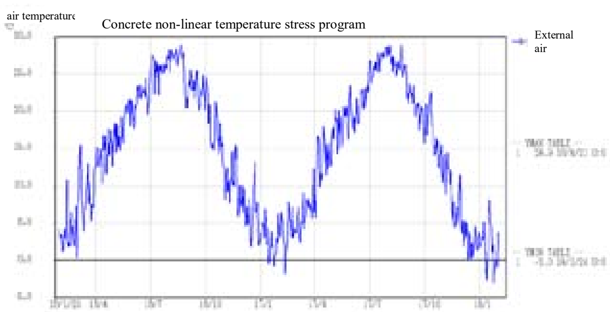

Fig. 8 : Measured external air temperature ata

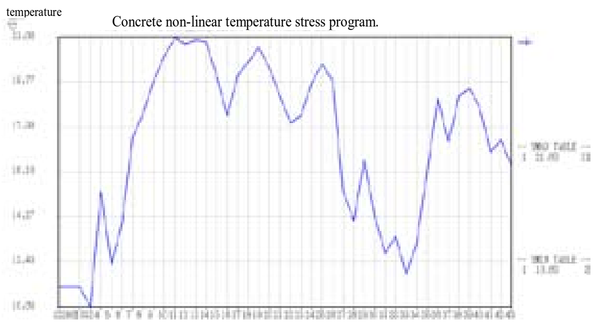

Fig. 9 : Measured placement temperatures

3.3.2 *Analysis results*

Figure 11 shows the temperature time history for point 4 as a representative value of the area colored yellow indicating a temperature of 25°C to 30°C (internal temperature) on the temperature distribution of Figure 10, and likewise point 2 as a representative value on the EL 125.0 m construction joint surface, etc. The internal temperature drops gently, whereas in contrast the external temperature drops rapidly due to exposure to the external air. The temperature difference is about 22°C. On the other hand, Figure 12 shows the distribution of the minimum values of the crack index. It was not possible to reproduce the position of cracks above the passage (it is considered that the thermal cracks occurred here because cold air entered the passage). However, areas with low crack index (crack index 1.44, probability of cracks 13.6%) were reproduced at the positions on the EL 125.0 m construction joint surface where cracks occurred. This demonstrates that these cracks were thermal cracks. Crack index time history is as shown in Figure13.

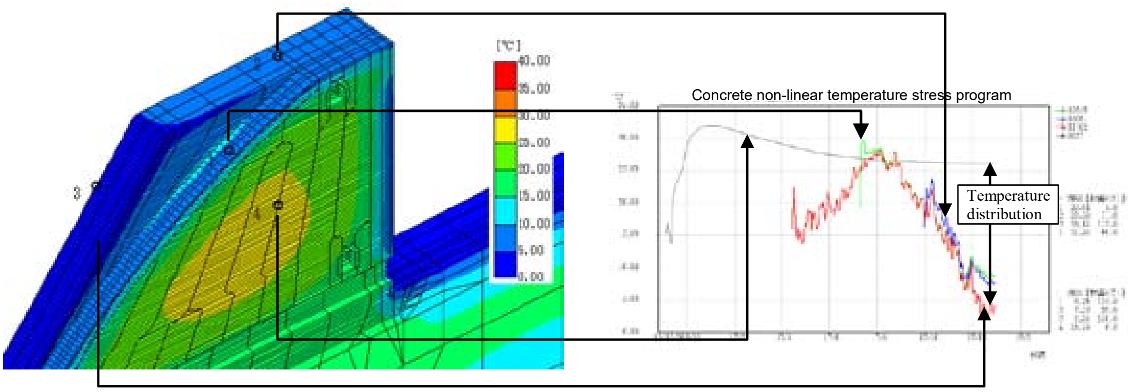

Fig. 10 : Temperature distribution (2017.12.31)

Fig. 11 : Temperature time history

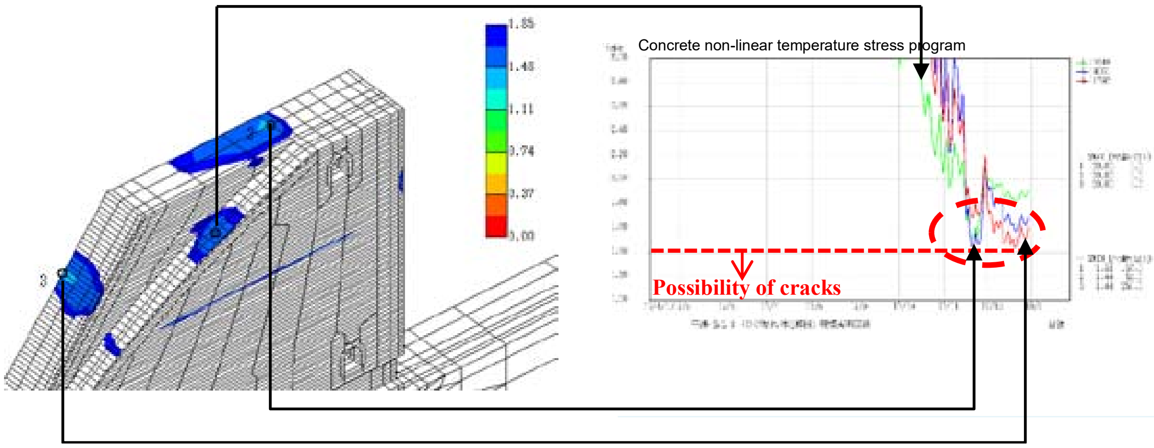

Figure 12. Crack index distribution (distribution of minimum values in the analysis period)

Figure 13. Crack index time history

4. COUNTER MEASURES AGAINST CRACKS

Countermeasures were taken against cracks in two stages: emergency measures to prevent cracks that had occurred from extending further as the air temperatures on the construction site dropped day by day and hour by hour, and permanent measures to repair cracks and unify the structure.

4.1 Emergency counter measures

It was inferred that the main cause was thermal cracks due to internal constraint, so the following emergency measures were taken so that the concrete would not be cooled by the external air.

– The EL 125.0 m construction joint surface, the overflow surface, and the wall surfaces were protected by installing thermal insulation material (t = 10 mm, polyolefin foam, thermal conductivity $\lambda_0 = 0.031$ W/mK).

– Strict control of the opening and closing of the doors on the passage openings was enforced, and another door was added to the inside of the doors to prevent entrance of cold air with the double doors.

4.2 Permanent countermeasures

4.2.1 *Injection of cracks*

Chemical milk made from ultra fine particulate cement (average 4 μm) was injected to fill cracks and unify the structure, and the status of filling was checked using check holes. The injection was carried out as follows.

Drill injection holes

↓ Injection holes were drilled using a rotary boring machine from the EL 125.0 m construction joint surface passing through cracks. The hole diameter was 66 mm, and the drilling angle was 60° down from horizontal.

Cleaning inside of holes

↓ The insides of the injection holes were cleaned with water.

Water flushing

↓ The water was flushed with a maximum pressure of 0.2 MPa

Injecting cement milk

↓ Cement milk was injected at a pressure of 0.2 MPa and a rate of pressure rise of 0.05 MPa/min or less.

Making certain

↓ After the rate of injection became 0 L/min at the prescribed injection pressure, the pressure was held for a further 30 minutes to make certain that injection was complete.

Filling the holes

↓

After making certain, the injection holes were filled.

↓

Drilling check holes

Check holes of diameter ϕ66 were drilled, flushed with water, and filled to check the filling.

4.2.2 *Providing reinforcement to prevent extension of cracks*

The cement milk was injected into cracks in order to unify the structure, but it was difficult to guarantee complete integrity of cracks by filling with the grout, so reinforcement was provided in addition to injection. The quantity of reinforcement was designed so that after placement of concrete the strain when the concrete temperature dropped from the maximum temperature to the final stable temperature could be borne by the reinforcement alone. Deformed steel bars D32 at 200 mm spacing were placed in 3 layers.

4.2.3 *Design of reinforcement to prevent extension of cracks*

The reinforcement to prevent extension of cracks was designed in accordance with the following concept.

Basic Equations

Temperature stress increment at cracks: $T(1) = \alpha \times \Delta T \times Ec \times A$

Temperature stress borne by the strengthening: $T(2) = \sigma s \times As$

Here T(1) = T(2), so the quantity of reinforcement per 1 m length of cracks (= per unit width 1,000 mm) **A**s is,

As = $(\alpha \times \Delta T \times Ec \times A)/\sigma s$

α: Linear coefficient of thermal expansion (= 8×10^{-6} /°C; test value)

ΔT: Temperature drop from maximum temperature (23.0°C, analysis value) to final stable temperature* (14.4°C) (= 8.6°C)

Ec: Young's modulus of concrete (20,000 N/mm^2)

A: Cross-sectional area of new lift (= lift depth 1,500 mm × unit width 1,000 mm)

σs: Allowable stress of SD345 reinforcement (= 180 N/mm^2)

As: Quantity of strengthening reinforcement (mm^2)

* that the final stable temperature is the annual average temperature (see Figure 14).

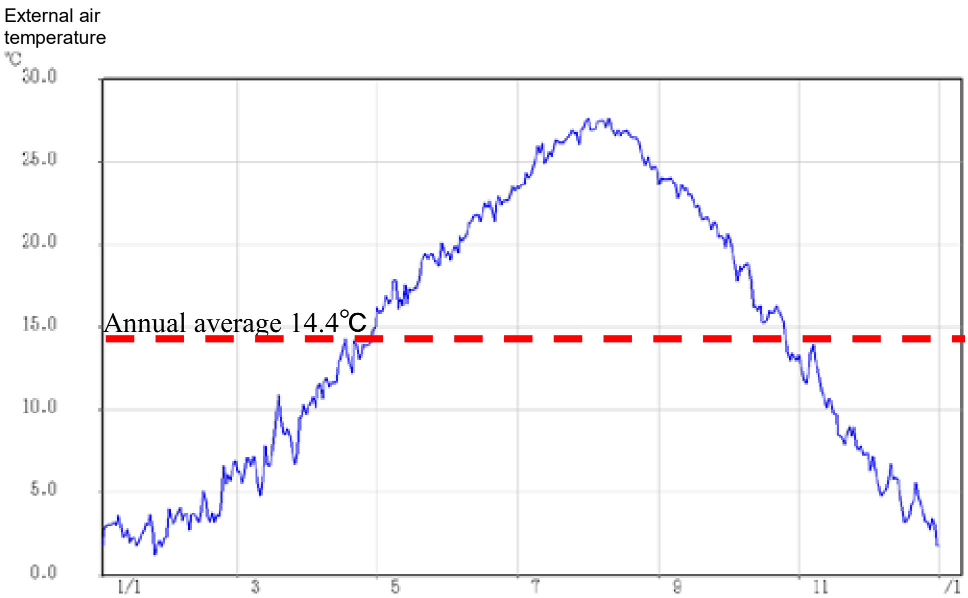

Figure 14. Daily average air temperatures (10 years average)

5. CONCLUSIONS

New dam construction was carried out taking measures to reduce the occurrence of thermal cracks to a probability of 15% or less (crack index 1.40), based on the results of analysis performed before the start of construction. It is considered that cracks were generally reduced, and the results of the analysis were achieved. However, some cracks occurred as reported here. The countermeasures based on the analysis were not able to completely prevent the occurrence of cracks. With the fluctuations in the weather in recent years the fluctuations in the air temperature are increasing, so subsequent verification analysis was carried out using the measured values of the parameters in the analysis (actual air temperatures, actual concrete placement temperature, actual concrete temperatures). It was confirmed that a probability of cracks of 15% or less that was the target of the analysis before construction was achieved.

The previous year a low elevation spillway had been constructed in an adjacent block, and cracks had been prevented, so it is considered that there was overconfidence in the analysis results. A probability of occurrence of cracks of 15% or less does not completely prevent the occurrence of cracks, and it is necessary to take sufficient measures, with plenty of time, such as protection with thermal insulation, etc., during the time when the concrete is still young and has not reached sufficient strength and before sudden cooling occurs.

Therefore, it is important to construct while constantly monitoring for cracks on the site. As far as possible, the crack index should not be 1.40, but should be taken with a margin. When cracks still occur, emergency countermeasures are taken so that the concrete surfaces are protected by installing thermal insulation material. After that, permanent countermeasures are taken so that the cement milk is injected into cracks in order to unify the structure. And reinforcement is provided in addition to injection.