Technique and Practice on Temperature Control and Crack Prevention for RCC Dam at High Altitude in Tibet

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Abstract: The dam in the DG Hydropower Station is currently the world’s highest roller compacted concrete gravity dam. The temperature control and crack prevention of concrete under special climatic conditions have become a key technical problem in dam construction. To avoid temperature cracks in the dam, the proportion of raw materials is determined in accordance with casting time, climatic conditions, and raw material performance parameters. Furthermore, the concrete mix ratio is optimized, and concrete with high cracking resistance, relatively low hydration heat, optimal VC value, and good rolling and bleeding properties is prepared. It effectively prevents the occurrence of temperature cracks in dams and solves the technical problem of temperature control and crack prevention for RCC dam construction in high-altitude areas.

1. Introduction
Since the 1980s, the technology of RCC dam construction has been widely studied and rapidly promoted in China due to its low cost and short construction period. However, the temperature control and crack prevention of RCC dams are still an important subject. Although the temperature control and crack prevention of RCC dams have developed and formed a complete theoretical system since the 1930s, the phenomenon of “no dam without cracks” remains worldwide[1]. Cracks in mass RCC dams are brought about by two factors. First, internal and external temperature differences cause compressive and surface tension stresses in concrete, resulting in temperature cracks; second, external humidity reduction accelerates the drying shrinkage of concrete, resulting in drying shrinkage cracks[2]. The dams of the Wudongde and Fengman hydropower stations adopt an intelligent water temperature control system for temperature control and crack prevention; this system has achieved good results and guaranteed project quality[3~4]. The Xiluodu and Laxiwa hydropower stations have avoided the occurrence of harmful cracks through a series of research[5~8]. In the Three Gorges Dam, a “personalized” water cooling scheme has been proposed and applied; this scheme implements weather, temperature control, and intermittent warning systems for concrete construction monitoring and refined comprehensive crack prevention measures, which have achieved remarkable results[9].
The DG Hydropower Station is located in a high-altitude, dry, and cold valley area with harsh climatic conditions and thus experiences difficulty in dam temperature control and crack prevention. Therefore, technical measures and methods must be targeted.

2. Project overview
The Dagu Hydropower Station located in Sangri County, Tibet Autonomous Region, is a second-class (2) project, mainly for power generation. The normal reservoir water level is 3447.00 m, the corresponding storage capacity is 552.8 million m³, and the dam site controls a basin area of 157,400 km². The average flow over the years is 1010 m³/s, and the installed capacity of the power station is 660 MW. The key buildings of the hydropower station are composed of water retaining, flood discharge, and energy dissipation buildings; diversion and power generation systems; and booster
stations. The barrage is an RCC gravity dam. The upper reaches adopt abnormal concrete + secondary RCC antiseepage, and the width of the antiseepage area is 5, 3.5, and 2 m from bottom to top. The dam crest elevation is 3451.00 m, maximum dam height is 117 m, dam crest length is 385 m, dam RCC is 937,000 m³, and normal concrete is 505,000 m³[10].

3. Climatic characteristics of the dam site
This project is located in the Qinghai–Tibet plateau climate zones, with basic features of low-temperature disturbance, thin air, wind, dry climate; large temperature difference between day and night, and strong solar radiation (>1500 w/m²). Dry season occurs from November to April, and the rainy season happens from May to October. The perennial average temperature in this region is 9.3°C, and the extreme highest and lowest temperatures are 32.5°C and −16.6°C, respectively. The annual average precipitation is 527.4 mm, the annual average evaporation is 2,084.1 mm, and the annual average relative humidity is 51%. The minimum relative humidity is less than 10%, and the annual average atmospheric pressure is 685.5 hpa. The maximum timing wind speed over the years is 19.0 m/s, the annual average sunshine hours is 265.7 h, and the annual maximum frozen soil depth is 19 cm[11].

4. High-altitude RCC dams face the challenge of temperature control and crack prevention
The climate conditions of the dam site are extremely unfavorable for the temperature control and crack prevention of the dam body; this challenge is mainly reflected in the following aspects: First, the outer surface of freshly poured concrete is subject to the sun’s strong radiation, wind, dry climate characteristics; moreover, surface moisture dissipation is fast, and tensile stress easily forms on the surface of the concrete, resulting in concrete and shrinkage cracks. Second, the evaporation of water in freshly poured concrete is fast, and the volume shrinkage is constrained by the old concrete surface; in addition, cracks are easily produced. Third, the temperature difference between day and night, and the frequency of sudden temperature drop, before the concrete reaches the design strength index, hydration temperature rise. Before the concrete reaches the design strength index, the hydration temperature rises and falls, and the internal temperature increases, leading to a large difference in temperature between inside and outside; such difference easily leads to temperature cracks.
To ensure the quality of the project, measures must be taken to control the temperature rise in the concrete proportion and raw materials and the water cooling, transportation, and pouring processes. The entire process, such as dam surface insulation, moisture preservation, and winter insulation, carry out research on the key technology of temperature control and crack prevention, the temperature control and crack prevention technology suitable for high-altitude area is summarized.

5. Design control standards for temperature control and crack prevention
The technical requirements for the design of an RCC dam scheme for temperature control and crack prevention are as follows:
- Dam quasistable temperature: 10°C.
- Storage temperature: control not to exceed 12°C.
- Basic allowable temperature difference ΔT: strong constraint zones < 12°C, weak constraint zones < 14.5°C.
- Temperature control standard for new and old concrete: RCC shall not be greater than 13°C. The new pouring concrete above the old concrete surface should rise continuously and evenly in short intervals to avoid the reappearance of old concrete.
- Temperature difference between inside and outside the RCC dam body: no more than 16°C.
- Maximum allowable temperature: RCC maximum allowable temperature [Tmax]: strong constraint zones ≤ 22°C, weak constraint zones ≤ 25°C, free zones ≤ 28°C.

6. Temperature control and anticracking technology
In accordance with the cause of cracks and the special climatic conditions in the region, the temperature control and crack prevention of the dam are mainly controlled from the following aspects:

6.1. Concrete mix proportion
In accordance with the casting time, climate conditions, and raw material performance parameters, to the proportion of concrete raw material composition must be determined, and the concrete mix ratio
must be optimized to achieve high cracking resistance, relatively low hydration heat, optimal VC value, and good milling and bleeding concrete.

1. The use of moderate heat Portland cement can slow down the strength growth of concrete in the early stage; such slow growth is beneficial to the control of the internal temperature of concrete.

2. The design age is 90 days.

3. Under the premise of ensuring the strength of concrete, the amount of fly ash is increased to the maximum extent to reduce the adiabatic temperature rise of concrete.

4. The VC value of RCC is easily affected by strong sunshine, low pressure, large temperature difference between day and night, dry conditions, strong wind, and other environmental factors unique to high-altitude areas. The VC value of RCC should not be treated as the same standard but should be dynamically adjusted in accordance with the temperature, humidity, sunshine, wind speed, and other conditions at different times of the day. According to the data summarized in 2019, the temperature in the morning and at night is relatively low, and the humidity is relatively high; thus, the VC value of the warehouse surface should be controlled within 1–2 s. When the temperature in the afternoon is ≥25°C and is under direct sunlight, the VC value of the warehouse surface loses rapidly, and the initial setting time shortens; thus, the VC value should be controlled within 5 mm (slump) within 1 s. Warehouse surface construction is controlled in accordance with the principle of “not sinking and rolling,” and the VC value is small.

5. Normal concrete should use low slump to reduce the amount of cementitious materials.

6. A modified machine mixing process is adopted to replace the manual grouting process and thus avoid the excess of manual grouting, which may easily lead to the increase in the hydration heat of concrete. Moreover, this process is conducive to the interlayer bonding quality of modified concrete in the impermeable area.

7. The optimal stone powder content is 20%; controlling the stone powder content within 20% ± 2% is advisable.

The mixture ratio of RCC used in the project is as follows:
### Table 1. Mixing ratio of RCC

| Designed strength grade | Gradation | Kind of concrete | Cement type | Design slump / VC value (mm) | Water-binder ratio | Content of fly ash (%) | Sand ratio (%) | Water consumption (kg/m³) | Aggregate ratio | Water reducing agent dosage (%) | Types of water reducer | Air-entraining agent dosage (%) |
|-------------------------|-----------|------------------|-------------|-------------------------------|-------------------|-----------------------|----------------|---------------------------|----------------|-------------------------------|----------------------|-----------------------------|
| C₉₀15W6F100             | three     | Middle fever     | RCC         | 0–3                           | 0.55              | 63                    | 34              | 88                        | 30:40:30        | 0.8                           | Naphthalene series       | 0.35                        |
| C₉₀20W8F200             | two       | Middle fever     | RCC         | 0–3                           | 0.50              | 50                    | 38              | 93                        | 50:50           | 0.8                           | Naphthalene series       | 0.30                        |
| C₉₀15W6F100             | three     | Distorted concrete | RCC        | 120–140                       | 0.55              | 60                    | 32              | 142                       | 30:30:40        | 0.8                           | Naphthalene series       | 0.012                       |
| C₉₀20W8F200             | two       | Distorted concrete | RCC        | 120–140                       | 0.50              | 50                    | 36              | 151                       | 50:50           | 0.8                           | Naphthalene series       | 0.012                       |

### Table 2. Material consumption per square (kg/m²)

| Designed strength grade | Gradation | Kind of concrete | Water consumption | Cement | Fly ash | Sand | Koishi | Middle stone | Dashi | Water reducing agent | Air-entraining agent | Apparent density (kg/m³) |
|-------------------------|-----------|------------------|-------------------|--------|---------|------|--------|--------------|-------|---------------------|-----------------------|------------------------|
| C₉₀15W6F100             | three     | RCC               | 88                | 60     | 100     | 739  | 430    | 573          | 430   | 1.28                | 0.560                 | 2420                   |
| C₉₀20W8F200             | two       | RCC               | 93                | 93     | 93      | 805  | 658    | 658          | /     | 1.49                | 0.558                 | 2400                   |
| C₉₀15W6F100             | three     | Distorted concrete | 142              | 104    | 155     | 687  | 438    | 438          | 584   | 2.07                | 0.310                 | 2548                   |
| C₉₀20W8F200             | two       | Distorted concrete | 151              | 151    | 151     | 746  | 664    | 664          | /     | 2.42                | 0.036                 | 2527                   |
6.2. Temperature control measures for raw materials and semifinished products

(1) Shading and heat preservation measures are adopted for the finished stock bin (thick and fine aggregate), and the stack height is over 6 m. Ground cage is adopted to take materials and thus reduce the effect of the temperature difference between day and night and extreme weather conditions. In the low-temperature season, it will not be frozen, and the aggregate temperature in the lower part of the pile is not less than 3°C.

(2) The storage capacity of cement is increased, and the cement temperature is reduced when mixing concrete.

(3) The dewatering time of sand is increased, and its moisture content is reduced so that more ice or cooling water can be added.

(4) In the high-temperature season, the coarse aggregate is air-cooled.

(5) Concrete mixing with ice or cold water. Coarse aggregate, sand, and ice content are the main factors affecting the temperature of the concrete outlet. According to the statistics of 2019, the temperature of coarse aggregate or sand rises by 1.0°C, and that of RCC rises by 0.30°C–0.52°C. For every 1.0 kg of ice added, the temperature of RCC decreases by 0.17°C–0.20°C. Therefore, in the concrete production process, the air-cooling effect of coarse aggregates must be strictly controlled, and ice or chilled water must be added as much as possible.

| Material                  | Coarse aggregate (G2–G4) | Sand/ S | Cement/ C | Water/ W | Ice (kg) |
|---------------------------|--------------------------|---------|-----------|----------|---------|
| C90 15W6F100 (Three-stage rolling) | Temperature change of raw material (°C) | 1.0     | 1.0       | 1.0      | 1.0     |
|                           | Temperature change of concrete (°C)  | 0.34    | 0.307     | 0.0198   | 0.048   | 0.192   |
| C90 20W8F200 (Secondary Rolling) | Temperature change of raw material (°C) | 1.0     | 1.0       | 1.0      | 1.0     |
|                           | Temperature change of concrete (°C)  | 0.513   | 0.334     | 0.0305   | 0.031   | 0.175   |

6.3. Temperature rise control during transport

In the process of transportation, a reasonable warehousing method must be selected to reduce transshipment. Two thirds of the RCC of the dam body in this project is directly transported into the warehouse by dump trucks, thus ensuring warehouse entry strength while reducing the temperature rise [12].

Dual carriageways are appropriate for transportation roads; if dual carriageways are not available, then a wrong lane must be set up at a suitable location, and a special dispatcher must be assigned, command to improve the efficiency of concrete transport vehicles and reduce concrete transport and waiting time for unloading.

Dump trucks, full pipes, and other concrete transport equipment all take the outer wall of a 3 cm-thick rubber sponge for insulation. The top of the transport dump truck is equipped with an insulated movable awning.

Through the above measures, recovery from the outlet temperature to the warehousing temperature can be controlled within 2°C.

6.4. Control of temperature rise during pouring

After entering the warehouse, paving and rolling are performed in time to improve the concrete pouring strength fully and minimize the interval time between floors. The interval time between RCC layers should be controlled within 6 h. In the high-temperature season, the dam section should be divided into several pieces for the construction of the flat layer paving method by reasonably dividing the silo and reducing the surface area of the silo. The interval time between layers should be controlled within 4 h.
The rolled concrete should be covered with light-colored strips of cloth or thin film for heat preservation and moisturizing. Spray and blanking machines are used to spray the warehouse surface to form a local microclimate, and the area that has been rolled and covered is sprayed on. At the back of the dam’s cantilever overturning steel template, a 10 cm-thick polystyrene board is pasted for template insulation. The dam is located in a valley, and strong sunlight occurs in the afternoon; thus, the cooling pipes are laid at night or in the morning. The afternoon high temperature and direct sunlight must be avoided in the construction of the cooling water pipe layer RCC; thus, the height of the cooling water pipe can be arranged 30 cm above or below the design layout height. Through the above measures, recovery from the warehousing temperature to the pouring temperature can be controlled within 2°C.

6.5. Keeping the concrete warm and moisturized after forming
The surface must be covered with moisture, and water must be sprinkled to cool it down. After the concrete is poured, the surface of the concrete is covered with geotextile, i.e., a colored strip of cloth or plastic film for sprinkling and maintenance, so that the surface of the concrete can be covered with water and cool down. It stays moist for a long time and has a good heat dissipation effect during the hot season. Facade maintenance. Mold removal is conducted during the high-temperature period in the daytime. The mold removal area is followed up by the heat preservation and moisturizing process in time. After the disassembly of the cross joint surface of the dam body, rubber and plastic sponge are used for heat preservation. Upstream and downstream facade maintenance combined with winter heat preservation measures in one forming.

The original design of dam concrete insulation is to paste polystyrene insulation board. Affected by strong wind, the polystyrene board tends to fall off; moreover, a gap is left during pasting. Under the action of solar radiation and strong wind, the concrete surface easily loses water and dries up, resulting in poor heat preservation and moisture effect. Through the comparison of heat preservation and moisture preservation process test, a new layer-type heat preservation and moisture preservation process is developed. The process is composed of a water spray tube, a PC film, rubber, plastic sponge, and three protective cloths; a customized layer-type is adopted and fixed with bolts. The process has the following advantages:
First, the heat preservation and moisture effect of this process meets the design requirements, ensuring that the temperature difference between inside and outside the concrete is ≤16°C. In addition, the surface humidity of concrete can reach more than 95%, thus ensuring the heat preservation and moisture effect of concrete surface and effectively avoiding the occurrence of temperature and dry shrinkage cracks on the concrete surface.
Second, the thermal insulation and moisturizing materials of this process are all flexible materials, which can be lapped. In addition, it is fixed by layering and bolts and does not fall off under strong wind conditions. After removal, no glue adhesions and secondary cleaning of the dam surface are needed, resulting in a beautiful appearance. Each material component is easy to recycle and can be reused, thereby saving energy and protecting the environment.
6.6. **Intelligent water cooling to reduce internal concrete temperature**

The cooling water pool and main branch pipes are wrapped with 3 cm-thick rubber plastic sponge as insulation material, and the snowy mountain melt water is used as the cooling water for the dam body. The water temperature of the snowy mountain melt water is 5°C–10°C during the high-temperature season and 1°C–5°C during the low-temperature season. When the temperature is below 0°C during the winter, the water supply is stopped.

When the cooling water pipe is laid, the keyway and buried PPR pipe are set in advance behind the dam to ensure that the water flow process is not disturbed by the construction. After the installation of the water pipe, the intelligent temperature control system is used for the intelligent water supply for the dam concrete to weaken the peak temperature of RCC strength growth and achieve temperature control and crack prevention. The cooling water pipes in the upper and lower abnormal concrete areas are properly encrypted.

According to the evaluation information of the internal cooling rate of the system, the overall control of the cooling rate is good, and the overall control is within 0.3°C–0.5°C per day. According to the statistical results of internal thermometer monitoring, the overall qualified rate is above 90%. 

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**Figure 1.** Schematic of layer-type heat preservation and moisturizing.
Figure 2. Implementation effect of reserved keyway

Figure 3. Intelligent temperature control effect monitoring
6.7. Concrete adiabatic temperature rise inversion
On the basis of the data of the intelligent temperature control system, the adiabatic temperature rise is inverted, the temperature process of the concrete that has been poured is fed back, and whether the calculated temperature process is consistent with the measured temperature process is observed. These results provide basis for the accurate prediction and evaluation of stress.

The adiabatic temperature rise of C9015W6F100 with three-stage roller compacting is
- Inversion value \( T = \frac{18.57}{1 + 4.587^t} \)
- Design value \( T = \frac{17.57}{1 + 3.286^t} \)

The adiabatic temperature rise of the second stage with metamorphosis C9020W8F200 is
- Inversion value \( T = \frac{28.08t}{t + 3.20^t} \)
- Design value \( T = \frac{23.08t}{t + 3.498^t} \)

Figure 4. Comparison of the measured and calculated internal temperature of the three-level rolling C9015W6F100
Figure 5. Comparison of the measured and calculated internal temperature of the secondary distribution metamorphosis C9020W8F200

The results show that the temperature curve calculated using the inversion parameters is consistent with the measured temperature curve.

6.8. Winter heat preservation

Concrete construction is suspended during the winter rest period (from December to February of the next year). The insulation materials for overwintering are divided in accordance with the upstream and downstream surface of the dam body, the sides of the dam body, the long intermittent surface of the dam body, and the holes of the dam body. Measures are divided in accordance with the climate characteristics and insulation requirements and compared with the technical requirements, as shown in the following table:

Table 4. Comparison table between overwintering insulation measures and original technical requirements

| Position                        | Original technical requirements               | Measures after optimization                              | Remarks                   |
|---------------------------------|-----------------------------------------------|--------------------------------------------------------|---------------------------|
| Upstream and downstream surface of dam body | Pasted 5 cm-thick polystyrene board on the surface | Water spray tube + PC film + 3 cm rubber and plastic sponge + flat steel + three anticloth | 1.5 m at the corner       |
| Dam side                        | Pasted 3 cm-thick polystyrene board on the surface | Water spray tube + PC film + 3 cm rubber and plastic sponge + flat steel + three anticloth |                           |
| Dam intermittent surface        | 15 cm-thick quilt                             | Water spray tube + PC film + 6 cm rubber and plastic sponge (one layer in vertical and horizontal directions) + three anticloth + scaffold tube and fastener weight |                           |
| Dam holes                       | 3 cm-thick polystyrene board closed           | 5 cm-thick thermal insulation curtain                   |                           |

Description: The main function of the embedded flower tube and PC film is to moisturize. The main function of the three-proof cloth is to prevent wind, rain, snow melt water into the dam body; it also has a fire protection function to avoid fire accidents in the work area.
Table surface pressure weight: The heat preservation and moisturizing materials are easily lifted due to the strong wind in the canyon during the low-temperature season, influencing the effect of heat preservation and moisturizing. Therefore, the scaffold pipe and fastener are connected into an integral 2 m × 2 m grid for easy installation and disassembly.

In the winter rest period of 2019, 17 temperature and humidity recorders were arranged in advance on the upstream and downstream surface of the dam, the elevation of the dam section, and the overwintering level for the monitoring of the thermal insulation effect during overwintering. The measured results at typical locations are as follows:

The monitoring results show that the temperature, humidity, and temperature gradient on the concrete surface show good effect, meet the design temperature control index, and avoid the occurrence of surface dry shrinkage and temperature cracks.
7. Conclusions

(1) Midhot Portland cement of 90 days design age is adopted along with increased fly ash content. Measures, such as small collapse degree and machine mixing and deformation, are also adopted to optimize the mix ratio of concrete and reduce the internal hydration heat of concrete.

(2) The temperature of cement entering the site is reduced ahead of time, and ice or cold water are mixed to reduce outlet temperature. In addition, measures, such as heat preservation and spray, are effectively controlled during the transportation and pouring process to control the temperature rise effectively and reduce the difficulty of temperature control in the later stage of the dam construction. Temperature control and crack prevention technology can effectively prevent the occurrence of temperature cracks in dams in high-altitude areas and solve the key technical problems of RCC dam construction.

(3) The vertical PPR pipe embedded in the dam body reduces water flow interference and uses an intelligent water supply to ensure the cooling water efficiency and concrete temperature control index. By using the new heat preservation, moisture, and wind proof technology of “spray pipe + PC film + rubber plastic sponge + flat steel + three protection cloth” on the surface of dam body, no harmful cracks are found after being exposed in the winter of 2019. The dam temperature control and crack prevention measures applied in the Dagu Hydropower Station achieved good results. Through the practice and summary of temperature control and crack prevention technology, dam concrete quality is ensured. This study presents the temperature control and crack prevention technology of roller compacted concrete dam in the Qinghai–Tibet Plateau and provides an important reference for the subsequent hydropower development of the Yarlung Zangbo River Basin.

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