Comparison and Selection of Thermal Insulation Materials for RCC Dam Construction in Dry and Cold Valleys at High Altitudes in Tibet

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Abstract. Effective temperature preservation and moisture retention measures are key techniques in ensuring concrete quality and preventing cracks formation in RCC dams and the concrete surface in the middle reaches of the Yarlung Tsangpo River in dry and cold river valleys. Insulation and moisture retention effect, construction technology, and cost of pasting polystyrene board, spraying foam polyurethane, and rubber plastic sponge insulation membrane on the dam concrete surface were compared and analyzed to determine the thermal insulation material with the best temperature preservation, best moisture retention effect, and high applicability. Finally, the rubber plastic sponge, which matched the trim strip process, was determined as the best insulation material. It features temperature preservation, moisture preservation, no secondary cleaning after removal, good appearance, and high secondary utilization rate. The results of dam overwintering monitoring and uncovering inspection in 2019 showed that the internal and external temperature differences and surface humidity indexes of concrete were within the design index value, and cracks were absent. The purpose of temperature control and crack prevention of dam concrete was achieved, and the material has high application value.

1. Introduction
RCC dams easily produce surface dry shrinkage and temperature cracks because of their large volume. Dry shrinkage cracks on the surface are difficult to repair, and the repair effect is poor. Temperature cracks can damage the integrity and impermeability of the structure, resulting in the decline of concrete durability and endangering the dam safety. Therefore, reducing and avoiding the occurrence of concrete cracks have been long-term concerns of dam builders. The large difference between internal and external temperatures is the main reason for cracks in dam body concrete. Thermal insulation must be performed in time after the dam is poured to prevent cracks in concrete due to changes in ambient temperature. The selection of an economical and temperature-control design index of thermal insulation materials can not only ensure the quality of the dam but also save construction costs.

In 1950s, the United States attached great importance to the surface temperature preservation of concrete. The Detroit Dam and Flat Top Rock Dam were made of foam plastic board and cardboard insulation, and the top of the Cable Pier Dam featured sand insulation. Japan also uses PVC sheeting and PVC film as surface insulation and maintenance material[1]. In the former Soviet Union, two-layer thick formwork was filled with particleboard as thermal insulation material, and some of them were precast concrete slab. However, many cracks still appear after the application of the above insulation materials.
In 1961, China began to focus on the problem of dam thermal insulation. At the initial stage, straw bags and straw curtains were mainly used as thermal insulation materials. However, these materials are easy to burn and cause fire; they can easily rot due to moisture, and they are not durable and do not meet the requirements of ideal thermal insulation materials. In northeast China, such as Hengren and Baishan, wood wool board has been used for thermal insulation. Taipingshao Dam has been sprayed with cement-expanded perlite for thermal insulation. Although it plays a certain role in thermal insulation, the insulation effect decreases sharply after being affected by moisture. After the 1980s, foam plastics became the main thermal insulation material. Foam plastics mainly include polystyrene foam board, thermal insulation quilt, polyethylene air cushion film, and polyethylene foam board [2]. In recent years, the thermal insulation and crack prevention of dams are usually achieved by using foam plastic board and paperboard insulation, PVC sheeting, PVC film, polystyrene foam board, heat insulation quilt, polyethylene air cushion film, polyethylene foam plastic, and polyurethane foam [1]. Dams such as Fengman Hydropower Station and Huangdeng Hydropower Station in China also use thermal insulation materials such as spraying foamed polyurethane and rubber plastic sponge coil. Polystyrene insulation board is used for thermal insulation of dam body concrete in accordance with the design requirements of the project. At present, the supporting construction technology for this method is relatively mature, and corresponding mature industry technical standards also exist in China.

2. Engineering situation
DG hydropower station is a second-class large (2) type engineering plant mainly for power generation located in SANGRI County, Shannan Prefecture, Tibet Autonomous Region. The normal pool level of the reservoir is 3447.00 m, and the corresponding storage capacity is 5.528 million m³. The control basin area of the power station dam site is 157,400 km², the annual average flow is 1010 m³/s, and the installed capacity of the power station is 660 MW. The dam crest elevation is EL.3451.0 m, and the maximum dam height is 117 m. It is the highest RCC dam under construction in the world, with a crest length of 385 m, roller-compacted concrete of 937,000 m³, and normal concrete of 505,000 m³.

3. Meteorological data
The project is located in the climate zone of Qinghai Tibet Plateau. The main climatic characteristics of the project are as follows: strong solar radiation (>1500 W/m²), strong wind (the maximum wind speed is 50 m/s, and the wind direction in the dam site canyon area is disordered), large temperature difference between day and night (the temperature difference between day and night is more than 20°C), dry (the average relative humidity for many years is 51%; the minimum relative humidity is less than 10%), high evaporation (2084 mm/year), and low rainfall (527 mm/year). The annual average air pressure is 685.5 hPa, the average sunshine hours is 2605.7 h, and the maximum frozen soil depth over the years is 19 cm.
Figure 1 shows that the large temperature difference between day and night in the project site (the maximum daily temperature difference is close to 30°C), which generally exceeds the requirements of the internal and external temperature difference standard of roller-compacted concrete <16°C and that of normal concrete <22°C during the dam construction period. The design technology requires that the temperature preservation material polystyrene insulation board be covered on the concrete surface for a long time before water storage, and flowing water (or sprinkling) is necessary for maintenance to avoid temperature cracks in concrete.

4. Comparison and application of thermal insulation materials
In the early stage of the project, the following problems were exposed during the application of polystyrene thermal insulation board in the 1# and 17# dam sections constructed in advance in accordance with the design requirements because of the special climate condition: The polystyrene board fell off under the influence of strong wind, and an inevitable gap was found in the middle of the bonded styrene board. This gap led to the loss of water and dryness on the surface of concrete, resulting in poor temperature preservation and moisture retention. Simultaneously, there was residual glue on the surface of concrete, which led to its poor appearance, and it needed to be removed again.

The thermal insulation effect of polystyrene board, cotton quilt, spraying foamed polyurethane, and rubber plastic sponge in the DG hydropower station was used to select the best thermal insulation material combined with several thermal insulation methods commonly used in domestic dams.

4.1. Comparison of thermal insulation materials

| Material name | Material properties | Price (yuan/m²) | Thermal conductivity (m.k) | Fire rating |
|---------------|--------------------|-----------------|---------------------------|------------|
| Polystyrene   | The white object is made of | General | 0.042 | Grade B3 flame |

Table 1. Comparison of thermal insulation materials.
4.2. Contrast test

4.2.1. Experiment

Polystyrene board insulation: On the basis of the size of the installation position, the layout of the polystyrene board was prepared to save materials and improve the construction speed before construction. The plastic extrusion plate was paved horizontally in the long direction to ensure continuous combination. The vertical staggered joint of the upper and lower rows of plates was 1/2 of the board length, and the local minimum staggered joint should not be less than 200 mm \(^3\). The environmental protection glue should be evenly applied on the polystyrene board with a brush. When pasting the extruded board, the plate joints should be squeezed tightly, and the adjacent plates must be flush. The gap between the control boards should not be greater than 2 mm during construction.

After the polystyrene board is installed, a 10 cm × 3 cm (high × long) groove is opened on the polystyrene board with a knife to install the probe of the temperature and humidity meter. The polystyrene board with the same thickness is applied with environmental protection glue for sealing after the installation.

Spray polyurethane insulation: Detailed analysis of climatic conditions, characteristics of polyurethane foam, and spraying process should be conducted to avoid problems that may occur in the process of spraying polyurethane before construction. Polyurethane should be sprayed in place at one time following the top-down or bottom-up spraying sequence. When spraying, polyurethane should be evenly dispersed. The probe of temperature and humidity meter should be installed on the concrete surface in advance.

The temperature preservation effect of cotton quilt is greatly reduced after water absorption. Cotton quilt is an inflammable product because of its water absorption property, so a comparative study on the temperature preservation performance of cotton quilt was not made.

Rubber plastic sponge thermal insulation: The innovative construction technology of spray pipe + PC film + rubber plastic sponge is adopted as the temperature preservation and moisture preservation layer to achieve the requirements of concrete surface thermal insulation and environmental protection.
At the same time, to ensure that the rubber plastic sponge is installed firmly, the tension bar hole of the formwork is turned up by a cantilever. After the formwork is removed, fixed bolts are used to connect with customized sleeve and flat steel bar to firmly fix the insulation and moisture retention layer without damaging the concrete surface and damaging the reinforcement.

![Diagram of temperature preservation and moisturizing process](image)

**Figure 2.** Temperature preservation and moisturizing process.

![Diagram of temperature preservation and moisturizing test](image)

**Figure 3.** Plane diagram of temperature preservation and moisturizing test.

### 4.2.2. Comparison of test results

**Table 2.** Comparison of temperature preservation and moisturizing effects.

| Time         | Atmospheric temperature and humidity | Glue paste polystyrene board | Spraying polyurethane | Water pipe + film + 5 cm rubber plastic sponge |
|--------------|--------------------------------------|-----------------------------|-----------------------|-----------------------------------------------|
|              | temperature /°C | humidity /% | temperature /°C | humidity /% | temperature /°C | humidity /% | temperature /°C | humidity /% |
| 2020/1/11 14:46 | 12.5 | 57.8 | 12.74 | 69.9 | 14.31 | 75.9 | 14 | 99.8 |
| 2020/1/11 19:15 | 2 | 42.5 | 0.23 | 68 | 0.81 | 72.5 | 0.5 | 100 |
| Date/Time          | Atmospheric Temperature | Glue-bonded Polystyrene Board | Spraying Polyurethane | Drainage Tube + Film + 5cm Rubber Sponge |
|-------------------|-------------------------|-------------------------------|-----------------------|-----------------------------------------|
| 2020/1/12 19:15  | 8.18                    | 65.2                          | 1.46                  | 59.7                                    |
| 2020/1/13 17:12  | 8.56                    | 74                            | 4.69                  | 59.8                                    |
| 2020/1/13 21:42  | -0.81                   | 79.9                          | 0.56                  | 46.7                                    |
| 2020/1/14 19:27  | 3.75                    | 82.7                          | 3.96                  | 58.8                                    |
| 2020/1/15 10:27  | -3.43                   | 81                            | 0.12                  | 64.9                                    |
| 2020/1/15 17:12  | 14.12                   | 69.5                          | 6.25                  | 63.4                                    |
| 2020/1/15 21:42  | 1.5                     | 90                            | 0.98                  | 68                                      |
| 2020/1/16 3:42   | 1.37                    | 86.7                          | 1.25                  | 64.1                                    |
| 2020/1/16 17:12  | 9.31                    | 83.2                          | 4.95                  | 59.1                                    |
| 2020/1/16 21:42  | 6.75                    | 63.2                          | 2.55                  | 58.7                                    |
| 2020/1/17 12:42  | 11.06                   | 72                            | 10.82                 | 62.9                                    |
| 2020/1/17 17:12  | 9.56                    | 79.2                          | 5.43                  | 69.7                                    |
| 2020/1/17 21:42  | 1.68                    | 82.2                          | 1.23                  | 68                                      |
| 2020/1/18 12:42  | 11.06                   | 81                            | 12.25                 | 59.3                                    |
| 2020/1/18 17:12  | 9.56                    | 69.5                          | 6.82                  | 58.8                                    |
| 2020/1/18 21:42  | 1.37                    | 27.8                          | 1.25                  | 46.4                                    |
| 2020/1/19 12:42  | 11.68                   | 34.1                          | 9.25                  | 41.9                                    |
| 2020/1/19 17:12  | -4.75                   | 39.9                          | 9.2                   | 42.7                                    |

**Figure 4.** Comparison of temperature preservation effect.
4.3. Conclusions

According to the test results, the following conclusions are drawn:

(1) From the perspective of the temperature preservation effect: The temperature preservation effect curves of the three materials were basically consistent.

(2) From the perspective of moisturizing effect: The moisturizing effect of rubber plastic sponge supporting measures was obviously better than the former two.

(3) From the construction technology point of view: The polystyrene board material paste can easily fall off, the appearance image is poor, and subsequent demolition must first clear the concrete surface, which is labor-consuming. Spraying polyurethane has the advantages of fast construction speed but high cost and environmental pollution during the later stage of cleaning. The surface of the concrete insulation with trim strip rubber plastic sponge is not polluted and the moisture retention effect is excellent when it is combined with a water pipe. Moreover, the construction installation and removal are convenient and the materials can be reused, leading to greater advantages compared with the former two.

In conclusion, rubber plastic sponge is the best choice as thermal insulation material for dam construction and concrete molding.

5. Detection of application effect of insulation in the winter break period

On the basis of the climate conditions and construction conditions in the winter break period of the project area, 17 thermometers were added on the surface of the dam to monitor the effect of winter insulation. After the winter break period in 2019, no cracks were found, thereby indicating the project’s quality.
In general, the effect of winter temperature preservation was good. When the insulation layer was opened for inspection, water droplets were evenly distributed on the PC film, and the moisture retention effect met the necessary requirements. The maximum internal and external temperature difference was basically 14°C–15°C, and the minimum difference was 2°C–3°C. Thus, these values met and exceeded the design index that the temperature difference between the inside and outside of
the roller-compacted concrete of the dam body shall not exceed 16°C and that of normal concrete shall not exceed 16°C.

6. Economic benefit analysis
The economic benefits of the three construction technologies were compared and analyzed. The area of the temperature preservation and moisture preservation test area was 18 m². Without regarding other costs, the following details are given below.

(1) When sticking polystyrene board for thermal insulation construction: According to the material unit price and the price of matching glue (15 yuan/piece), the material cost is 30.91 × 18 (polystyrene board) + 12 × 15 (glue) = 736.38 yuan, and the labor cost is 350/8 × 6 × 3 = 787.5 yuan, totaling 1555.88 yuan.

(2) When spraying foamed polyurethane: the material cost is 120 × 18 (polyurethane) = 2160 yuan. Two workers need 5 h to complete the construction, and the labor cost is 350 / 8 × 5 × 2 = 437.5 yuan, totaling 2597.5 yuan.

(3) When using the trim strip rubber plastic sponge technology: The cost of material is 18 × (1.26 + 64.34) (film and rubber plastic sponge) + 18 × 12 (customized flat steel) + 3 × 1 (PVC hose) + 6 × 1.2 (bolt) = 1407 yuan. Three workers require 5.5 h to complete the task, and the labor cost is 350/8 × 5.5 × 3 = 738.38 yuan, totaling 2145.38 yuan.

Table 3. Comparative analysis of economic benefits.

| Technology                  | Unit Price /yuan | Area/m² | Material cost/yuan | Labor cost/yuan | Total/yuan |
|-----------------------------|------------------|---------|--------------------|-----------------|------------|
| Paste polystyrene insulation board | 30.91/m²         | 18      | 736.38             | 787.5           | 1555.88    |
| Spray foaming polyurethane  | 120/m²           | 18      | 2160               | 437.5           | 2597.5     |
| Trim strip rubber plastic sponge | 64.34/m²        | 18      | 1407               | 738.38          | 2145.38    |

As shown in the table above, the cost of sticking polystyrene insulation board is low, the cost of trim strip rubber plastic sponge process is high, and the cost of spraying foam polyurethane is high.

7. Conclusion
Through a comparative analysis of the effects of temperature preservation and moisture retention, construction technology, and economic benefits of polystyrene board, spray polyurethane, and rubber plastic sponge, the following conclusions were drawn:

(1) Sticking polystyrene board is the most cost-effective technique in the field, but it can easily fall off due to the influence of the environment and climate in the application process. The moisture retention effect is poor, and it is easy to cause dry shrinkage cracks on the surface. After removal, the secondary utilization rate is low and the image’s appearance is poor.

(2) Spraying polyurethane has the best temperature preservation effect and the highest cost among the analyzed techniques, and its moisturizing effect is lower than that of rubber plastic sponge. Its environmental protection degree is poor, and subsequent cleaning cost is also high.

(3) Spraying polyurethane has the best moisturizing effect, high cost, and slightly lower insulation effect than that of spraying polyurethane. However, it does not need to be cleaned again after removal. It has a good appearance and high secondary utilization rate. The cost can be greatly saved depending on the calculation of single reuse.

In summary, the trim strip rubber plastic sponge insulation technology has good temperature preservation and moisture preservation effect, convenient construction, convenient material recovery of each component, and secondary utilization. Moreover, it offers energy conservation and environmental protection. At present, the construction technology has been successfully authorized by the construction method of the Tibet Autonomous Region and the national utility model patent. Through large-scale application in the dam of the DG hydropower station in Tibet, the winter
monitoring and uncovering inspection results of the dam in 2019 showed that the internal and external temperature differences and surface humidity index of concrete were within the design index value, and crack was absent. The purpose of temperature control and crack prevention of dam concrete was achieved, which proves its applicability and superiority and greatly promotes the technology of temperature preservation and moisture preservation of dam concrete surface. It has high popularization and application value.

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