

Temperature Control for the Gomal Zam RCC Arch-Gravity Dam

Implementation of pre- and post-cooling for construction of a massive roller-compacted concrete structure

by Chongjiang Du

For both conventional concrete and roller-compacted concrete (RCC) dams, temperature control is the primary method and common practice for reducing thermally induced tensile stresses and thus preventing uncontrolled cracking during the construction period. Although significant progress has been achieved, temperature control of RCC is still an intricate task for dam builders. Because RCC needs to be cooled to a final stable temperature, post-cooling is usually necessary. However, installation of the cooling system can be challenging in RCC because of its fast construction rate and heavy compaction equipment. This article describes the temperature control measures used during the construction of the Gomal Zam RCC arch-gravity dam, which was constructed from 2008 to 2012.¹

The Gomal Zam arch-gravity dam is on the Gomal River in the North-West Frontier Province (also known as Khyber Pakhtunkhwa), Pakistan. Primarily built for irrigation, flood control, and power generation, the dam is 231 m (758 ft) long and 133 m (436 ft) high. The dam has a vertical upstream face and an inclined downstream face with a slope of 1:0.6 (V:H), and its maximum base width is 78 m (256 ft). The left and right half of the dam have curvature radii of 180 and 240 m (590 and 787 ft), respectively. The four-bay spillway comprises 17.5 m (57 ft) wide bays incorporated into the dam. Moreover, a bottom outlet is arranged to sluice sediment from the reservoir.

Arch dams use arch action and the compressive strength of the construction material to resist loads. Transverse (radial) contraction joints are used to control cracking during construction, and these joints must be grouted prior to initial reservoir impounding to ensure monolithic behavior and to give the necessary arch action.²⁻⁴ The Gomal Zam Dam included two transverse contraction joints spaced 60 m (197 ft) apart, starting from the elevation of 50 m (164 ft) above the

dam-foundation interface and extending to the top of the dam.

The dam is located in a subtropical climate region with a mean annual temperature of 25.5°C (78°F). The maximum and minimum recorded temperatures near the site are 49.4 and -3.3°C (121 and 26°F), respectively, and the record shows that the diurnal temperature variation is rather great. In 6 months of the year, the mean monthly temperature exceeds 25°C (77°F). In June and July, the mean monthly temperature exceeds 35°C (95°F). The river water has a mean annual temperature of 19.1°C (66°F). The mean annual rainfall is 252 mm (10 in.), the mean annual pan evaporation is 1785 mm (70 in.), and the mean annual wind velocity is 1.5 m/s (5 ft/s).

Temperature Control Requirements

The temperature control requirements were established on the basis of a detailed thermal study and included consideration of the site-specific RCC mixture, local climatic conditions, and construction schedule.⁵ The specification required that concrete temperatures at placement were not to exceed 18°C (64°F) for placements in the strong restraint zone ($H = 0$ to $0.2L$, where H is the distance above the foundation and L is the base length [78 m]). The temperature limits increased to 23 and 25°C (73 and 77°F) for placements in the weak restraint zone ($H = 0.2L$ to $0.4L$) and zero restraint zone (H above $0.4L$), respectively. The peak temperatures in the three zones of the dam body were not to exceed 34, 41, and 44°C (93, 106, and 111°F), respectively. The determined allowable placement temperatures are listed in Table 1.

In the strong restraint zone, RCC was continuously placed layer by layer and lift by lift. In the zones above the strong restraint zone, the time interval between two successive layers was limited to no more than 28 days. The temperature difference between two successive lifts was not to exceed 6 to 10°C (11 to 18°F), depending on the restraint zone. In

addition, the temperature gradient between the interior concrete and the surface of the dam was not to exceed 16 to 18°C (29 to 32°F) in the first 14 days after placing.

RCC Mixture Proportions and Construction Techniques

The dam comprises 395,400 m³ (517,164 yd³) of RCC and 100,700 m³ (131,711 yd³) of conventional concrete. The conventional concrete was mainly applied in the power intakes (first and second stage), bottom outlet, and spillways (first and second stage). Two main RCC mixtures were selected (Table 2), based on laboratory and full-scale trials. Class F fly ash produced in Karachi, Pakistan, was used for the production of the RCC and conventional concrete mixtures.

The adiabatic temperature rise of RCC Mixture C16 was 21.8°C (39°F) at 28 days. The RCC was placed in 300 mm (12 in.) thick layers for lift thicknesses of 1.5 to 4.2 m (5 to 14 ft). The flat-layer and sloped-layer methods were both applied in the RCC placements, but the sloped-layer method was applied in most parts of the dam to reduce the number of cold joints. A grout-enriched vibrated RCC was used for the upstream and downstream facing at the RCC interface with the rock abutments and in the areas around openings.

It should be noted that the proposed cement and fly ash contents indicated in Table 2 were each reduced by 5 kg/m³ (8 lb/yd³) for Mixture C16 and 7 kg/m³ (12 lb/yd³) for Mixture C20. The reduction of cementitious materials was based on compressive strength test results over the initial 6 months of

construction. Before the reduction, the average 28-day compressive strength was generally higher than 18 MPa (2610 psi) for Mixture C16. After the reduction, the average 28-day compressive strength decreased but was not less than 15 MPa (2180 psi). The later test results verified that the 180-day strength was definitively higher than the specified 16 MPa (2320 psi).

For the production of RCC and conventional concrete, two 3 m³ (4 yd³) mixers with twin horizontal shafts provided a nominal capacity of 180 m³/h (235 yd³/h). Four 750 tonne (827 ton) silos were used for the storage of cement and fly ash (two silos for each material). Nominal capacities for coarse aggregate and sand production were 280 and 70 tonne/h (309 and 77 ton/h), respectively. During the construction period, 8000 m³ (10,464 yd³) of coarse aggregate and 4000 m³ (5232 yd³) sand were stored in the stockpiles. The actual maximum concrete placement rates were 3150 m³/day (4120 yd³/day) and 32,100 m³/month (41,985 yd³/month).

Thermal Study

The required temperature control measures were based on a thermal study that included the local conditions, construction schedule and procedures, and test results for the project-specific RCC mixtures. The temperature and thermal stress distribution in the dam were obtained through computer modeling. Thermal stress calculations included consideration of the creep and autogenous volume change of the concrete. The main findings were⁶:

- Precooling and post-cooling of the dam concrete were necessary;
- Two transverse contraction joints were needed;
- The initial peak temperature of concrete would occur at 2 to 4 days after placing;
- An initial stage of post-cooling could effectively remove the heat of hydration of cement, lowering the maximum temperature rise of the RCC by 4 to 8°C (7 to 14°F);
- The peak temperature ranges (from 34.5 to 36.3°C [94 to 97°F] in the areas above the strong restraint zone) would occur in the hot season;

Table 1:
Allowable placement temperature

Month	1	2	3	4	5	6
Mean air temperature, °C	14.0	15.4	18.0	24.3	31.5	35.8
Placement temperature, °C	18.0	18.0	18.0	24.3	25.0	25.0
Month	7	8	9	10	11	12
Mean air temperature, °C	35.2	33.8	32.0	27.8	21.8	15.8
Placement temperature, °C	25.0	25.0	25.0	25.0	21.8	18.0

Note: °F = 1.8 × °C + 32

Table 2:
Main RCC mixtures

Strength class	Cement, kg/m ³	Fly ash, kg/m ³	Water, kg/m ³	Sand, kg/m ³	Coarse aggregate, kg/m ³	Admixture, kg/m ³	Maximum size aggregate, mm	Application area
C16/20 at 180 days	91	91	109	685	1427	1.5	75	Dam interior
C20/25 at 180 days	105	105	116	730	1333	1.7	37.5	Upstream ribbon of 6 to 10 m

Note: Strength class is specified using cylinder/cube strength; 1 kg/m³ = 1.7 lb/yd³; 1 mm = 0.04 in.; 1 m = 3.3 ft

- The peak temperature in the dam might be 2 to 3°C (4 to 5°F) higher than that specified in the temperature control criteria, but the tensile stresses in each part of the dam would meet the required stress limits; and
- Sudden temperature drops might cause surface cracking. Thus, protection of fresh concrete surfaces with insulation was deemed necessary during sudden temperature drops. Figure 1 shows a section of the calculated temperature and thermal stress distribution.

Temperature Control Measures

Extensive measures for temperature control of the RCC dam were proposed and performed in terms of proper concrete technology, construction techniques, and structural methods. These measures included⁵:

- Using large coarse aggregate (maximum size of aggregate of 75 mm [3 in.]) and high-range water-reducing admixture to reduce the cementitious materials content;
- Using a high Class F fly ash content and using low-heat cement (Type II) to limit the heat of hydration of the concrete mixture;
- Limiting the cement temperature to below 60°C (140°F) prior to charging the mixers;
- Keeping the aggregate pile heights at more than 6 m (20 ft);
- Chilling mixing water to 2 to 4°C (36 to 39°F) for RCC production;
- Maintaining the RCC mixture temperature at the batch plant at 2 to 3°C lower than the specified placement temperatures;
- Placing the concrete possibly at night, during early mornings, or on cloudy days during hot weather;
- Using awnings to shade vehicles transporting concrete mixtures;
- Applying fog (or water mist) in the placement area to create a local climate with low temperature and high humidity;
- Precooling of aggregates using chilled air circulation;
- Post-cooling of the RCC dam using embedded cooling pipes;
- Insulating concrete surfaces with fiber blankets to prevent heat gain from ambient heat; and
- Installing reinforcement in the upstream face to limit crack widths.

Precooling of concrete aggregate

At the batch plant, RCC mixtures were required to be 16°C (61°F) or less. To attain this goal, coarse aggregates had to be precooled to 2 to 4°C, and mixing water was chilled to 2 to 4°C. The aggregates were precooled in two stages using chilled air.

In the first precooling stage, the aggregates were conveyed into a storage silo, located about 20 m (66 ft) from the batch plant. Chilled air at around 0°C (32°F) was blown into the storage silo at a rate of 180,000 m³/h (47.6 million gal./h), and the aggregates were cooled to 10°C (50°F) in 55 to 60 minutes. Three screw ammonia compressors with a total capacity of 1746 kW (1.50 × 10⁶ kcal/h) were employed to chill the air.

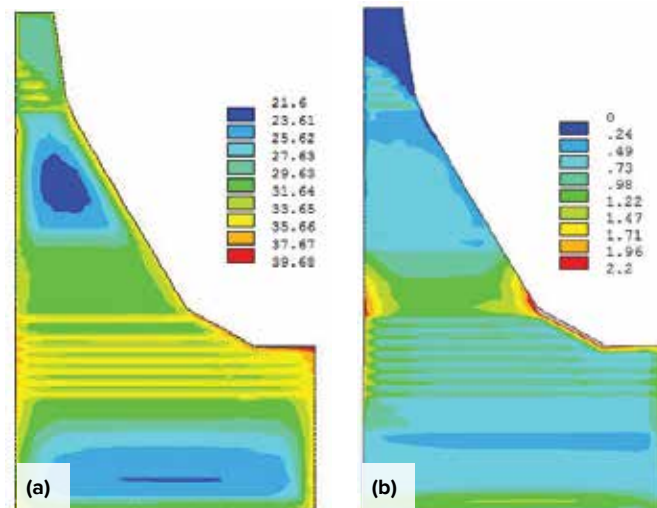


Fig. 1: Crown cantilever section data: (a) maximum temperature envelope in °C; and (b) principal thermal tensile stress envelope in MPa (Note: °F = 1.8 × °C + 32; 1 MPa = 145 psi)

In the second precooling stage, the 10°C aggregates were delivered from the storage silo into the bins at the batch plant by a conveyer belt system, where the aggregates were further cooled to 2 to 4°C within 55 to 60 minutes by blowing chilled air at -8 to 12°C (18 to 54°F) at a rate of 120,000 m³/h (31.7 million gal./h). The total capacity of the two screw ammonia compressors used in this stage was 1164 kW (1.0 × 10⁶ kcal/h).

Subsequently, the precooled aggregates were discharged into the two 3 m³ mixers. Mixing water was precooled with a 500 kW (0.43 × 10⁶ kcal/h) chiller. The batch plant was capable of producing precooled RCC at a rate of 100 m³/h (131 yd³/h) or nonprecooled RCC at 120 to 150 m³/h (157 to 196 yd³/h). The precooling and mixing of concrete were continuous processes. To prevent heat gain from ambient conditions, the storage silo, conveyer belt system, and batch plant were insulated with expanded polystyrene foam boards.

Post-cooling

Post-cooling was necessary to limit the peak temperature and to lower the dam temperature to the final stable temperature so that the transverse contraction joints could be closed by grouting. Post-cooling of RCC dams has proven to be more difficult than that for conventional concrete dams because:

- Installation of the cooling pipes must not delay RCC placement operations; and
- RCC placement and compaction operations must not damage the embedded pipes.

An extensive study showed that these prerequisites can be fulfilled by proper design and construction management as well as selection of suitable materials for the cooling pipes.⁷ In the following sections, the essential aspects of the post-cooling methodology for the Gomal Zam Dam are summarized.

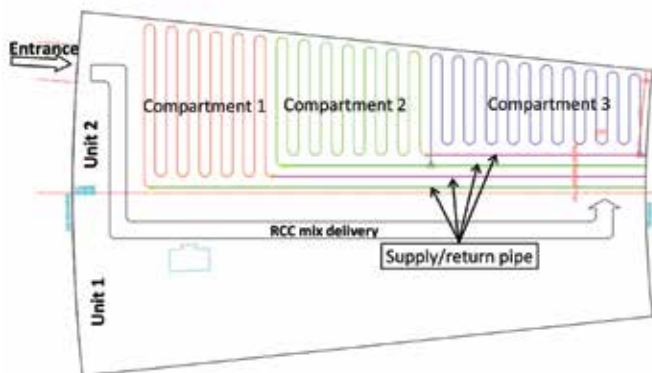


Fig. 2: Partition of construction units and cooling compartments

Selection of the pipe material

Steel cooling pipes were deemed unsuitable because installation would be time-consuming and labor-intensive. High-density polyethylene (HDPE) pipes were selected because of the following characteristics:

- Light weight—A 200 m (656 ft) long HDPE pipe weighs only 35 to 40 kg (77 to 88 lb);
- Flexible and coilable—HDPE pipes have a minimum bending radius of 200 to 250 mm (8 to 10 in.) without the need for separate elbow fittings;
- Long stock lengths—HDPE pipes are typically supplied in lengths of 200 to 250 m (656 to 820 ft) per reel, which minimizes joints;
- High strength—HDPE pipes have a tensile strength in excess of 20 to 25 MPa (2900 to 3630 psi) and a high Mullen burst strength of not less than 3 to 10 MPa (435 to 1450 psi);
- High elongation capacity—HDPE pipe has a minimum elongation at break of 200%;
- Low friction—The smooth internal surfaces of HDPE pipes minimize friction losses and thus reduce pumping energy requirements;
- Cost-effective—HDPE pipe is much less expensive than steel pipe; and
- Safe and well-known—HDPE pipes are nontoxic and have been safely used for more than half a century.

Partitioning of construction

The RCC placement area was divided into at least two units, as shown in Fig. 2. This permitted installation of cooling pipes in one unit while RCC placement was underway in the other unit. To minimize conflicts at the unit interface, cooling pipes in the second unit were installed two or three layers higher than pipes on the first unit.

Each construction unit was partitioned into several cooling compartments such that the total length of the cooling pipe in each compartment did not exceed the length of one reel (240 m [787 ft]). No pipe joint was required and thus installation time was reduced. Moreover, the cooling efficiency was not degraded by excessively long cooling pipes.

Connections to supply and return pipes

The HDPE distribution pipes had 32 mm (1.25 in.) outside diameters and 2 mm (0.08 in.) thick walls. The HDPE supply and return pipes had 40 mm (1.5 in.) outside diameters and 3.0 mm (0.1 in.) thick walls. Distribution pipes were connected to supply and return pipes using prefabricated three-way (Tee) steel pipe fittings. Each HDPE pipe end was softened by heating, pushed over the steel pipe, and fastened with steel wire.

Pipe installation

The cooling pipes were placed in a 1.5 x 1.5 m (5 x 5 ft) grid on horizontal and on sloping layers of RCC. Reinforcing bars were used to “staple” the pipes onto the fresh RCC surfaces. The 4 to 6 mm (0.16 to 0.24 in.) diameter bars were pre-bent into U-shapes and were inserted into the RCC at a 2 to 4 m (7 to 13 ft) spacing for straight portions. Three staples were used at 180-degree bends. Before installation (and again after being covered with a layer of the RCC mixture), the pipes were leak tested using water or air at a pressure of 0.1 MPa (15 psi). Leaks were repaired prior to compaction of the RCC.

After the pipe grids were in place, a 250 to 300 mm thick layer of RCC mixture was placed over the grid by dumping and spreading the mixture from one side of the cooling pipe network. After the final leak test was conducted, bulldozers, trucks, and rollers were allowed to pass over the protected pipes (Fig. 3). This was a critical step, as the layer of RCC protected the pipes from the heavy equipment and avoided serious plastic deformation of the pipes that could have resulted in leakage or blockage of the flow of cooling water.

Operation of the cooling pipes

Starting 6 hours after compaction of an RCC layer and continuing for 14 days, cooling water was circulated (at a supply temperature of 14°C [57°F]). The RCC temperature was reduced to the specified final temperature using a final stage of post-cooling performed at least 1 month prior to the grouting of the transverse contraction joints. In some areas, the cooling system was also operated in an intermediate stage to decrease the temperature difference between interior and surface concrete and reduce the thermal stresses in the dam while the modulus of elasticity of RCC was relatively low. In addition, cooling water was retained in the cooling pipes for several days after a cooling stage to fully use the residual cooling effect of the water.

The flow rate through a single pipe system was about 0.8 m³/h (211 gal./h). The direction of flow was reversed every 12 or 24 hours to reduce temperature gradients within each lift as it cooled. The acceptable rate of temperature drop was not to exceed 1°C (2°F) per 24 hours. Also, to minimize the risk of thermal shock in the concrete, the temperature difference between the RCC and the cooling water was limited to 25°C (45°F).



Fig. 3: Heavy equipment working on the covered cooling pipes

Curing

Soon after compaction, the top surfaces of the RCC layers were insulated with fiber blankets (to prevent heat gain from hot ambient conditions) or continually wetted by water spraying. As the surface temperature was generally higher than the ambient temperature, exposed surfaces were cured with river water to dampen the daily fluctuations in the surface temperature, further reduce the temperature rise of the RCC mass, and prevent surface cracking from drying shrinkage. The curing was carried out for 28 days or until the surfaces were covered with the subsequent layer of RCC.

Temperature Measurements

Mixture temperatures were measured every 2 hours at the batch plant and every 4 hours at the placement locations. Thermal sensors were also installed in the dam during RCC placement. Readings were taken every 4 hours during the initial rise period and thereafter at regular intervals. Typical measured temperature histories at 35 m (115 ft) above the foundation are shown in Fig. 4, from which it can be seen that the peak temperature in the dam remained within the specified 44°C (111°F) limit.

The thermal sensors and the water in the cooling pipes were used to monitor the RCC temperature over the long term. Water in the cooling pipes attained the temperature of the surrounding concrete when left to stand for more than 5 hours, and thereafter it was run off at the supply/return pipe. The highest temperature of the released water indicated the temperature of the surrounding concrete.

Other Observations

Fogging, timing of post-cooling, and heat gain during transport

Figure 5 shows fog produced from a hand-operated fog gun. Fogging created conditions that reduced the heat gain and moisture loss in the placed RCC. While ambient temperatures ranged from 35 to 40°C (95 to 104°F), the

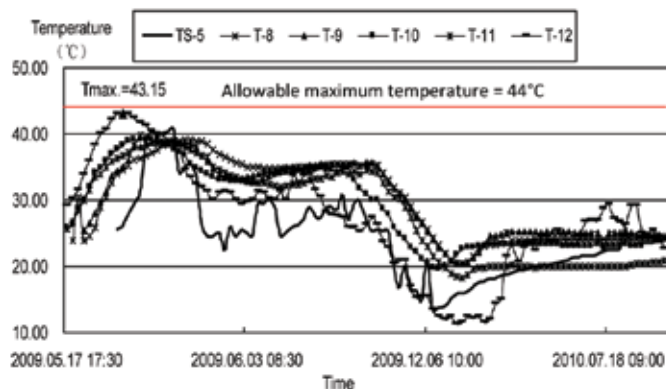


Fig. 4: Typical temperature histories of six thermal sensors at 35 m (115 ft) above the foundation (Note: °F = 1.8 x °C + 32)



Fig. 5: Fog (water mist) produced from a hand-operated fog gun

fogging reduced local temperatures by 5 to 8°C (9 to 14°F) and created a local relative humidity at the placing area of 80% or more.

The timing of the post-cooling was also found to be important. The peak temperature of RCC was reduced by 4 to 8°C at Gomal Zam Dam when cold water was circulated in the embedded cooling pipes within 6 hours after RCC compaction. Thermal sensors indicated that the temperatures mostly fell within the specified range, except in some areas where the circulation of cooling water in the grids was delayed to 2 days after the RCC compaction.

In hot weather (when ambient temperature exceeds 30°C [86°F]), a pre-cooled concrete mixture can gain a great deal of heat from the ambient environment. Although the delivery vehicles were shaded with an awning during transport of concrete over a distance of only about 1.7 km (1.1 miles) from the batch plant to the dam, a temperature rise of about 2°C was observed in the RCC.

Conclusions

Temperature-control measures used in the construction of the Gomal Zam RCC arch-gravity dam were appropriate for preventing thermal cracking of RCC in a hot weather region. The precooling of aggregates and mixing water ensured the

specified low placement temperature, and the post-cooling of the placed RCC decreased the peak temperature and allowed the timely achievement of the final temperature required for joint grouting. The procedures developed for the project ensured that the installation of the cooling pipes did not interfere with rapid RCC construction, and they safeguarded the cooling pipes from damage by heavy equipment.

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