THERMAL INDUCED CRACKING PERFORMANCE OF RCC DAMS

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SUMMARY

Designers of roller-compacted concrete (RCC) dams are invariably concerned with control of thermal-induced tensile stresses and thus the possibility of uncontrolled cracking which can lead to leakage related problems in the dam. Complex computer generated thermal analyses help design engineers with understanding the situation that lead to design measures for mitigating potential cracking. However, much can also be learned from the actual performance of RCC dams in service.

In this paper, nine case studies are presented, including the authors' experiences from three other large RCC dams. The case studies presented focus on dams that have experienced some cracking. Many of these dams were early generation RCC dams that either did not include transverse contraction joints or included widely spaced joints. The case studies were selected mainly to illustrate the lesson to be learned from the design and the actual situation that occurred once the dam was placed in service. Repair methods and an insight into concrete cooling methods to include costs are presented.

From the case studies and authors experiences, the main observations or conclusions are presented in addition to recommendations for improved crack control for new RCC dams.

1.   BASICS OF THERMAL INDUCED CRACKING

The fundamentals of how heat generated by the hydration of cement and fly ash can lead to cracking of concrete structures has been fairly well known for decades. After the concrete is placed at a certain temperature, hydration of the cementitious materials raises the internal temperature of the material to a peak. In the process, the concrete may gain or lose heat due to external effects such as air

and or water temperature on the concrete surfaces as well as from the adjacent foundation or abutment rock. The concrete eventually cools to some stable temperature and in the process a volume reduction occurs. This end point is usually the annual average temperature at the site with some seasonal variations and can take a number of years.

If the volume reduction is restrained externally by the rock foundation or internally by a hot interior of the concrete dam or other mass concrete structure, sufficient tensile strains can develop causing the concrete to crack. Cracks can occur with a temperature drop of as little as 11 deg. C from the peak concrete temperature for early age or lean, weaker mixtures to as much as the generally accepted 20 deg. C or more for stronger concrete. While a surface crack induced by an internal restraint may be narrow and not penetrate the mass much to start, it can propagate to be a wider crack that continues to the downstream face of a dam due to further thermal effects, high crack tip stresses or other loads with time.

2.   INTRODUCTION TO THERMAL ANALYSIS FOR RCC DAMS

A thermal analysis for an RCC dam, or any concrete dam, can range from a sophisticated computer aided finite element analysis to hand computational methods. The US Army Corps of Engineers (USAGE) in its Technical Letter No. 1110-2-542 "Thermal Studies of Mass Concrete Structures" lists three levels of thermal analysis, increasing in complexity. In Annex 2 of this publication, a mass gradient (cross canyon) analysis procedure and example is presented. In Annex 3, an example of a Level 2 analysis, for both a one-dimensional finite element mass gradient and surface gradient analysis, is given. For a Level 3 analysis, the designer is referred to ETL 1110-2-536 where the most complex thermal analysis methodology is discussed.

These more complex solutions can produce the temperature regime with time for each layer of RCC placed. If the input parameters are reasonably correct, the program can predict quite well the peak temperature, its location, when it occurs together with the resulting tensile strain with time.

Now, as design engineers, what we really want to know are two main things to complete our plans and specs. They are (1) the average spacing and location of transverse contraction joints to control the cracks, and (2) the absolute maximum or the average maximum RCC placing temperature to be specified. Even though an analysis may indicate no cracking, or a wide joint spacing, or possibly that certain cooling methods may not needed, we may feel we need to be more conservative. It seems we need to look further into our assumptions and their potential variations.

Just for a Level I analysis many factors need to be assumed, calculated or be obtained from published data. These factors include:

1.   The annual average temperature at the site.

2. The temperature of each RCC mixture component when delivered to the mixer.
3. The specific heat of each material in the mixture.
4. The modulus of elasticity of the foundation rock (Er) and possibly how it varies with elevation.
5. The modulus of elasticity of the RCC (Ec) and possibly how it varies with time.
6. The external mass gradient restraint factor and its variation with respect to its distance from the plane of restraint, which is usually the dam/foundation contact.
7. Possibly the more complex internal restraint factor, keeping in mind that the sum of both restraint factors can not exceed 1.0.
8. The adiabatic heat rise of the mixture at a certain age (say 180 days), including an assumption of the heat generating capability of the fly ash compared to the cement.
9. The heat that is lost or gained to the adjacent air, water or foundation material as well as heat gain in mixing and transporting the RCC to the placing area.
10. The coefficient of thermal expansion of the RCC and its tensile strain capacity at a certain age.
11. The average crack width to be used in calculating the number of contraction joints and thus the average spacing of the joints and, especially,
12. The planned construction schedule with respect to average weather conditions, per month or other time period.

In consideration of all the factors and their variations, it is difficult to feel real confident in the accuracy of the results. However, one can come up with reasonable results through an understanding of the fundamentals and the input of likely factors.

Now this is the time for the design engineer to temper his mathematical analysis with engineering judgment. Some of this judgment can be obtained by studying the actual cracking performance of RCC dams in service compared to the analysis. It is the authors hope that the case studies presented along with the observations and conclusions derived from the actual performance of these dams as well as recommendations will help produce better performing RCC dams.

3. THERMAL PERFORMANCE OF RCC DAMS – CASE STUDIES

What actually occurred with respect to thermal related design compared to actual cracking performance is presented herein for nine RCC dams ranging in height from 18 to 90 m. The dams were selected for study based on what could be learned from their performance, or lack of it. The basic data on the dams is contained in Table 1, including the annual average temperature at the dam site as well as the specified limit on RCC placing temperature.

Table 1
Data on RCC Case Study Dams

Dam & Construction Period	Owner / Engineer	Max Height m	Crest Length m	RCC Volume m³	Cement & Flyash kg/m³	Annual Ave. Site Temp °C	Maximum Placement Temp °C
1. Galesville (1985) Azalea, OR. USA	Douglas County/Morrison Knudsen Engrs. (URS Corp)	50	290	161,000	53+51	12.3	21.1
2. Upper Stillwater (1985-87) Duchesne, UT. USA	Central Utah Water Cons. Dist./US Bureau of Reclamation	90	815	1,125,000	79+173	2.9	10.0
3. Elk Creek (1987-88 halted) Medford, OR. USA	US Army Corps of Engrs. Portland Dist. a)Construction as built, b)Construction as planned	25 / 76	365 / 786	267,000 / 796,000	70+33	12.5	21.2
4. Hudson River #11 (1993) Baldwin, GA. USA	Banks County/Soil Conservation Service (now NRCS)	21	160	26,000	119+87	16.1	18.3+8.3 (Spec +)
5. Big Haynes (1996) Conyers, GA. USA	Conyers-Rockdale Authority/Jordan, Jones & Goulding (now Jacobs)	27	427	71,600	42+42	16.3	23.3 (24 hr ave.)
6. Deep Creek #5D (2009) Yadkinville, NC. USA	Yadkin County, North Carolina/Schnabel Engineering	18	454	38,000	89+89	13.6	21.1 (24 hr ave.)
7. New Victoria (1991) Perth, Australia	Water Authority, Western Australia	52	285	121,000	80 + 160	18.6	18.0
8. Arriaran (1992 Northern Spain	Diputacion Foral de Gipuzkoa	58	206	110,000	85+135	14.4	22.5
9. Salto Caxias (1998) Southern Brazil	Companhia Paranese de Energia	67	1083	912,000	80+20	20.3	15.0

1-Galesville Dam. This early generation RCC dam was designed without any water stopped transverse joints. A coal-tar based elastomeric membrane sprayed on the upstream face did not have sufficient elasticity to bridge the subsequent occurrence of seven major cracks through the dam. Cooling the RCC consisted of producing aggregate in winter and chilling the mix water to limit the maximum RCC placing temperature to the specified 21.1°C.

A delay in the start of RCC placement pushed the majority of the RCC being placed into warmer weather in June and July, 1985, thus increasing the peak internal temperature of the RCC mass. Surface cracks were noticed 60 days following completion of the top most layers which were placed during the hottest time of the year. Then, unusually cold weather hit the site causing a larger differential temperature between the cooler surface and the hot interior of the RCC

mass. It is presumed the cracks did not extend into the mass too far at that time. It is known that it takes less energy to propagate an existing crack than create a new one. These cracks then extended to the downstream after the cross canyon thermal shrinkage took effect.

Of interest is the location of two cracks. One is through gallery adit to the right of the spillway and another near the middle of the spillway notch. This indicates that as the concrete shrinks in the cross canyon direction, cracks will most likely occur at areas of reduced section.

2-Upper Stillwater Dam. Because this RCC dam is located high in the Utah mountains, where the annual average temperature is only 2.8℃ above freezing, a maximum placing temperature of 10℃ was specified. Concrete cooling measures included producing aggregate in the cooler part of the year, use of flaked ice in the mix water, placing mostly at night from 8 pm to noon and injection of liquid nitrogen at times. Use of liquid nitrogen on a regular basis was not deemed cost effective.

After the dam was completed in August 1987, 13 cracks developed in the dam at an average spacing of 49 m (see Fig. 1).

Ultimately, the number of cracks increased to 23 with a reduction in the average spacing to 35 m. In addition to the thermal related contraction, a number of the cracks may have been initiated by a horizontal downstream movement in the foundation rock of 10 mm after the reservoir water load was applied to the dam.

Fig. 1
Aerial view of Upper Stillwater Dam, Utah showing cracking

A finite element computer analysis by the design team predicted cracking, but indicated the cracks would not penetrate the RCC mass by more than 6 m

from the upstream face.

Waterstopped joints at 4.6 m centres were initially proposed, but sealing the joint in the horizontal slip-formed concrete face was difficult, costly, and would slow down construction at the site where cold weather limited the effective construction season to about five months per year. Because the reservoir would be lowered annually, it was thought any cracks could be repaired from the upstream face, if needed.

Crack repairs have been made on several occasions with varying results and costs. The US Bureau of Reclamation first decided to repair the widest crack (6.6 mm) at Sta. 25+20 (see Fig. 2) and three narrower cracks in 1990 using a stable hydrophilic polyurethane resin at a cost of about US$600,000. This method only proved partially effective and not a long term solution.

Portland cement grout was also not really effective due to its lack of elasticity to accommodate seasonal opening and closing of a crack.

Two more major crack repair related contracts were awarded in 2003. The first for about US$800,000 was to provide a safe staging area on the left abutment for the main dam remediation contractor. The second contract for approximately US$9 million consisted of three different repair methods.
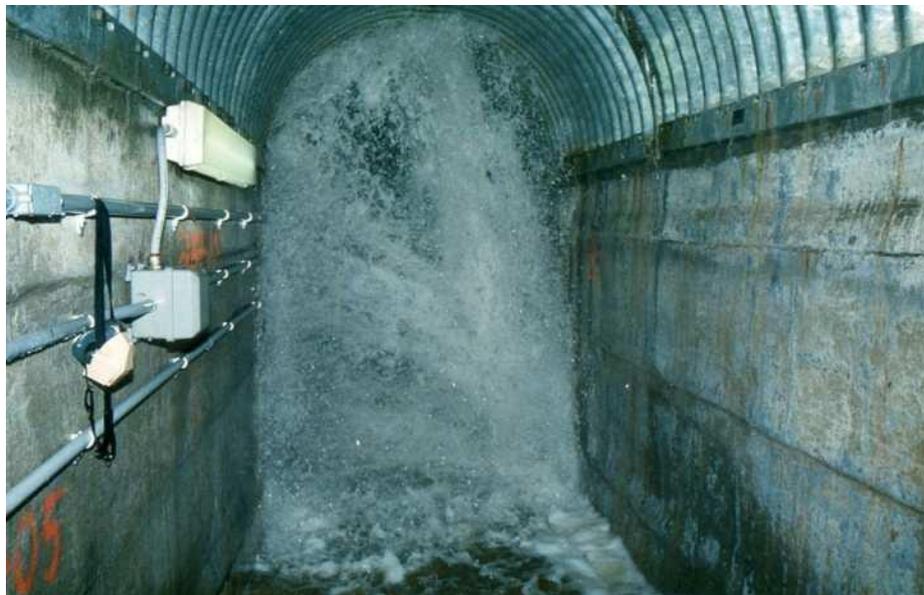

Fig. 2
Leakage in gallery through major crack at Upper Stillwater Dam

Installation of a positive internal membrane was the fix selected for the three widest cracks, including the one at Sta. 25+20 which was now nearly 30 mm wide due to erosion from water passing through the crack. Here a corrugated stainless steel membrane 4.3 m wide was installed to completely cover this as well as two other major cracks. Vertical 150 mm nominal diameter holes were drilled into the RCC similar to a secant wall to produce a 114 mm wide slot for insertion of the

membrane in 6.1 m lengths. The steel membrane sections were welded together to produce three effective cutoff membranes varying in depth from 48 to 57 m. Hot bitumen was poured into the slot to encase the membrane and its enlarged ends fixed by cement grout to accommodate expansion and contraction of the membrane.

This contract also consisted of chemically grouting seven cracks with drains installed behind the remediation grouting. Seven more cracks had only drains installed downstream of them to relieve water pressures in the dam.

3-Elk Creek Dam. The design by the U.S. Corps of Engineers Portland District to help control thermal related contraction consisted of placing ten water stopped transverse joints at a maximum spacing of 90 m across the planned 786 m wide dam. Most of the RCC was to be placed in cool weather where peak RCC temperatures were reduced by a reported 19℃ co mpared to hot summer placement, which was not allowed. However, due to a rare hot spell in April 1987, some RCC placement did occur during hot weather. Still the RCC was placed below the specified limit of 21.1℃. In October 198 7, a court order permanently stopped all work on the dam with only 25 m of the 76 m high structure completed.

Three uncontrolled cracks occurred later between the widely spaced transverse joints. The cracks were located (a) near the centre of the depressed spillway section, (b) adjacent to the reinforced concrete outlet works structure and (c) at a change in the slope of the foundation rock. All the crack locations are at a plane of reduced cross section or a potential stress concentration.

4-Hudson River #11 Dam. The design for this dam included PVC membrane faced precast concrete panels for seepage control, but no transverse joints. Cooling measures used by the contractor to meet the specified maximum RCC placing temperature of 18.3℃ included sprinkling a ggregate stockpiles, use of flaked ice in the mix water and limiting RCC placement to nine hours at night.

Still, during June 1993, the noted cooling methods could not keep the RCC temperature below the specified limit.

The owners then decided to proceed with higher placing temperatures, up to 26.7℃ and accept the consequences rather than susp ending RCC placement until the cooler time of the year. Except for one major crack, cracking observed on the downstream face was minor. The single wide crack is located about 0.6m inside the right end of the spillway and intersects the right gallery adit (see Fig. 3). Cracking at this location was not surprising as it is where there is a reduction in cross section due to the adit opening as well as close to a potential stress concentration where the dam's alignment turns abruptly downstream.

It was concluded by the design engineers that there was no conclusive evidence that any additional cracking occurred solely due to the increased RCC placing temperature. The thermal situation was aided somewhat when the measured peak interior temperature had been reduced by a greater heat loss to the atmosphere than the 25% loss assumed in the calculations.

Fig. 3
Crack at Hudson River No. 11 Dam, Georgia

5-Big Haynes Dam. This RCC dam is unique is that it was designed as seven separate RCC monoliths due to foundation conditions varying from rock to compacted soil. Joints that could accommodate movement both horizontally and vertically separated the monoliths which averaged 53 m in length.

The specified weighted limiting average temperature of 23.3°C over a 24 hour period without the introduction of liquid nitrogen was difficult to meet. This was mainly because construction delays pushed RCC placement into the hotter summer months. Prior to the onset of hot weather, the only cooling method used was the introduction of bagged or block ice into the mix water. A single all-in gradation aggregate stockpile while produced in cooler weather could not be further cooled effectively by shading due to the large size of the pile.

Approximately 20% of the RCC required further cooling during hot weather. Liquid nitrogen was introduced into the first lift each day to help with maintaining the RCC temperature below the weighted average maximum. Then, more liquid nitrogen was introduced when the RCC approached the temperature limit. The ice in the mix water reduced the RCC temperature about 0.6°C and the nitrogen by about 1.1 to 1.7°C. The cost of cooling in 1996 was about US$5.50/m^3 for the RCC cooled that included the cost of the nitrogen.

Intermediate cracks formed in at least 3 of the monoliths. These cracks were mainly attributed to settlement of the concrete section on a non-rock foundation.

6-Deep Creek Dam #5D. A Level 1 Corps of Engineers thermal analysis spaced the transverse joints mainly at 18 m centres for the 226 m long RCC portion of this composite dam that includes an earthfill portion on the left abutment.

The specification recognized that the average placing temperature in a 24 hour period was more technically correct than a strict maximum RCC placing temperature. Thus, the RCC placing temperature was allowed to reach 22.8°C for a period up to 4 hours as long as the weighted average did not exceed 21.1°C.

The design which also included face joints spaced at 4.6 m in the grout enriched RCC (GERCC) facing effectively controlled thermal related cracking except for one crack. The crack occurred about 4.6 m from an induced and water stopped transverse joint close to the right abutment. This uncontrolled crack was determined to have been caused by a small foundation anomaly that reduced the relatively narrow section near an area of high foundation restraint.

7-New Victoria Dam. Conditions dictated that the 121,000 m3 of RCC had to be placed in the summer of 1991. With a specified maximum placing temperature of 18°C the RCC had to be cooled by 10°C. Six metho ds were used to achieve a reduction in the temperature of the RCC as placed.

The methods consisted of (1) shading aggregate stockpiles, (2) sprinkling aggregate stockpiles for evaporative cooling, (3) chilled mix water at 4°C, (4) chilled water flowing down the conveyor feeding coarse aggregate up into the mixer holding bin, (5) injected liquid nitrogen into the Portland cement while being transferred from the delivery trucks to the storage silos, and (6) liquid nitrogen being introduced into the mix at three conveyor transfer points after it came out of the continuous RCC mixing plant.

Fig. 4
New Victoria Dam, Western Australia

The dam (see Fig. 4) included five transverse joints with a spacing of up to 75 m. Two uncontrolled cracks initially developed between the relatively long joint spacing. One was in line with the gallery entrance (adit) and another between the end of the gallery and the right abutment. Both cracks were subsequently grouted.

Records from the contractor indicated the actual cost of cooling all the RCC, as well as 13,000 m3 of conventional concrete, was A$6.80/ m3 or 10.5% additional cost to the RCC in place.

8-Arriaran Dam. The designers of this unique appearing RCC dam located in the Basque country of Spain performed an extensive literature search and complex thermal analysis in two phases to design for the potential thermal induced cracking in the structure.   Based on the analysis, two joints, spaced at 65.7m and then 61.0m starting from the left abutment, were installed. .

Upon completion of the dam in Nov. 1992, two uncontrolled vertical cracks were detected in the central portion of the dam. One year later, further cross canyon shortening produced another crack near the middle of the left hand block. All the cracks were located close to some weakened plane in the body of the dam where stress concentrations are likely to occur. The locations were near the gallery adit, conduits encased in conventional concrete and the intersection of the upper gallery with the abutment.

Conclusions developed by the designers from the actual performance compared to the thermal analysis indicated (a) the cracks were thermal induced as expected, originated at the foundation contact and propagated upward (b) the joints should have been spaced closer together and (c) it is important to simulate structural irregularities in the finite element model. and locate the contraction joints near the zones indicated with higher tensile stresses.

9-Salto Caxias Dam. The thermal cracking performance of Brazil's largest volume RCC dam is of interest because of the construction schedule. In addition operation of the dam during construction played a major role in the development of three major cracks (see Fig. 5).

Fig. 5
Salto Caxias Dam, Southern Brazil

The 1,083 m long dam is divided into three main parts (1) a gated spillway section atop RCC on the right side, (2) a 280 m long river bed section in the middle and a non-overflow section at the left abutment.

Transverse joints were installed in the spillway section at 20.5 m spacing. For the other two RCC sections, full section transverse joints were installed at 40m spacing, with partial transverse joints induced through the section for only the upstream and downstream thirds, in between the main joints. Only flaked ice in the mix water was used for cooling the RCC to below a reported 15 deg. C.

Due to the potential for high flows in the Iguacu River during the rainy season, overtopping the central river bed section was pre-planned. This portion of the dam was overtopped during construction five times. A maximum overflow of about $5,000m^3/s$ caused no significant damage. RCC placement on the left abutment section continued through these overflow events.

By keeping this portion of the dam lower than the remainder of the structure, the upper portion RCC placement was started during the hot summer weather eight months after completion of the RCC below. The new RCC was thus placed on top of an RCC surface that had cooled naturally by losing heat to the atmosphere as well as by the overflowing water.

The location of three major cracks is of interest. All three cracks are in the central river bed section where the RCC was placed last. One crack is near the left end of the section where the foundation rises creating a slightly smaller cross section. Another crack is in the first block adjacent to the previously placed spillway section where a stress concentration is likely. The third crack is located about halfway between the other two cracks and coincident with a partial transverse joint to relieve an excess cross canyon tensile stress.

These cracks were repaired soon after completion in 1999 with a variety of materials and mixture proportions. In general, the initial repairs were not successful in the long term and the owner undertook further repairs in 2006.

A further problem was encountered with some of the partial joints in the left abutment where the central third of the width of the cross section of the dam was left uncut, with the expectation that a crack would develop through, propagating from upstream and downstream to join up as a single crack/joint. In actuality many did not meet up with the result that a crack propagating from downstream to upstream, intersected the upstream face about 1-2m away from the waterstop resulting in an uncontrolled 'crack/joint' and consequent leakage

3.   SOME OTHER ADVERSE THERMAL EXPERIENCES

The Authors have, over the years, experienced some particular thermal phenomena which designers need to be conscious of as discussed below:

1-Cadiangullong Dam, Australia (43 m high, 110,000 m³ RCC, 380 m long). The transverse contraction joints (placed typically at 20-30 m spacing - depending on topographical and geological features) did not all open at the same time. The first one to open took the majority of the contractions, opening 8 mm with others opening later about 5 mm and some only 2 mm. Three of the early opening joints with wide openings showed leaks passing the PVC waterstop, indicative of a tear occurring through the PVC.

It would appear that joint construction by the usual procedure of cutting and inserting of a 'joint inducer' plate, or PVC sheeting, through the RCC to provide a plane of reduced tensile resistance is somewhat variable, with result that the weakest contraction joint opens first, taking up more contraction than those which open later.

2-Kinta Dam, Malaysia (90 m high, 930,000 m³ RCC). Here transverse joints were designed to be placed at 30 m centres and the upstream 4 m of RCC cooled to 20°C, the remainder of the dam being placed un-c ooled, reaching up to 30°C, all as determined by a detailed thermal stress analysis undertaken using ANSYS. The analysis showed the critical case was thermal shock cracking of the upstream face on first filling of the reservoir based on a 9 month RCC placing period. To prevent cracking the tensile strength of the upstream GERCC facing and adjacent RCC had to achieve 1.0 MPa at 90 days (see Fig 6). The contractor objected to any cooling of RCC, volunteering rather to reduce the spacing of the joints to 20 m, which still would not prevent cracking on first filling. His actual RCC placing time overran that expected during design from 9 to 22 months. When reservoir impoundment eventually took place, the tensile strength of the RCC facing was twice that required and consequently the predicted face cracking never occurred!

Fig 6
Kinta Dam, Ipoh Malaysia

A lot of design effort went into the thermal stress analysis based on the best expectations at that time, but in the end the actual situation proved quite different, as is often the case.

3-Pangue Dam, Chile (120 m high, 640,000 m³ RCC). A detailed thermal stress analysis determined the transverse joint spacing of 40 m, with the width of the last monolith block on each abutment being about 45 m (see Fig 7). Some months after impoundment, an inclined crack developed almost midway along the last block on the left abutment. The maximum height of the block was 30 m, reducing to zero. The crack was inclined in towards the abutment and normal to the axis of the dam. The last block on the opposite abutment had a max height of 70 m, reducing to 6 m but did not crack.

Fig 7
Pangue Dam, Southern Chile

Despite the results of a thermal stress analysis it would seem prudent to reduce by one-half, the joint spacing for the upper blocks where the height to block width ratio is significantly different to the remainder of the dam as analysed.

4.   MAIN OBSERVATIONS AND CONCLUSIONS

1.   Major thermal-related cracks are basically vertical, through the entire dam section, and may be of sufficient width to pass water at times. Because RCC dams invariably have a traditional gravity dam shape, these vertical cracks are not considered detrimental to the structural stability of the dam.

2.   Cracks in an RCC gravity dam may not have been caused solely by thermal induced tensile stresses. In some cases, reservoir induced horizontal movements in the foundation or differential settlements in a non-rock or low modulus rock foundation as well as concrete shrinkage due to loss of water may have contributed to the cracking.

3.   All transverse cracks do not initiate at the same time, nor are they of the same width. While a constant crack width is used in a simplified thermal analysis, measured crack widths can vary by a factor of more than 4 between the

widest and narrowest crack width in a transverse joint. Similar to concrete pavement joints, the first cracks observed tend to be the widest in the long run.

4. The most common cause of greater than anticipated cracking than predicted by a thermal analysis is a delay of construction schedule that pushes RCC placement into the warmer summer months resulting in a higher peak temperature in the RCC' mass than used in the analysis.

5. Average crack spacing for stronger RCC tends to be greater than lower strength concrete due to its increased tensile strain capacity. Because the total length reduction needs to be accommodated by a lesser number of cracks, the average width is greater. These wider cracks are a greater problem if they pass water.

6. The location of uncontrolled cracks tend to be at planes of reduced cross section or stress concentrations such as:

   a. Through the gallery entrance adit.
   b. In the centre and at times near the ends of the spillway notch.
   c. High in the dam near the abutments where there is greater foundation restraint together with a reduced section.
   d. Protrusions of the foundation rock into the dam.
   e. Adjacent to a conduit penetrating the dam, or
   f. Near a change in the axis of the dam.

7. Repair of wide uncontrolled cracks can be quite expensive, especially if the reservoir cannot be completely lowered for repairs. At Upper Stillwater Dam, the total cost of various methods of crack repair has exceeded $7 million.

8. The cost for providing an equal reduction in RCC placing temperature is not constant. The use of chilled water or ice in the mixing water provides the lowest cooling cost per degree. The use of liquid nitrogen is considered expensive and may not provide sufficient cooling benefit in relation to its cost.

9. Surface cracks due to a high thermal gradient between a hot interior and a cool surface may not initially penetrate far into the surface. However, they may turn into full section cracking as it is easier to propagate an existing crack than initiate a new one.

10. While a complex computer thermal analysis can be quite accurate in predicting temperatures with time as the RCC is placed layer by layer, they are less accurate in predicting crack location and width.

5.   MAIN RECOMMENDATIONS

1. In order to reasonably control thermal-induced cracking in an RCC dam, the designer needs to consider both pre-cooling measures for the concrete and also the installation of transverse contraction joints.

2. If the construction schedule will permit, producing aggregate in the winter and restricting RCC placement to nights and the cooler part of the day or year is invariably the most effective and least costly temperature control method.

3. The limiting maximum placing temperature for the RCC should consider the annual average temperature at the site, the function of the dam, and the cost of extreme cooling measures, if too low an RCC placing limit is specified.

4. Rather than specifying a strict maximum placing temperature for the RCC, consideration should be given to specifying a limiting average temperature over a 1 or 3 day period with a higher placing temperature allowed for a short period of time each day. In this manner, the contractor can better plan his cooling method and placement schedule with an eye toward cost reduction, without increasing cracking potential.

5. Cooling should be pre planned by the contractor for the worst case weather scenario especially with respect to cooling of aggregates. If additional cooling is required at the last moment, low cost cooling methods may no longer be available.

6. Transverse joints should include a waterstop and drain, be relatively easy to install, not affect RCC placement to any great extent and use low cost materials to produce a weakened plane. Considerable care should be taken in installing waterstops. There are too many cases in all types of concrete dams of improperly installed waterstops leading to excessive leakage at the joint and costly repairs.

7. Transverse joints should be strategically located and need not be spaced equally across the dam. See Observation/Conclusion #6 for possible location of transverse joints to better control cracking. Recently, quite a few designs have used an average spacing of about 20 m.

8. Sealed or waterstopped joints in the facing concrete (where used) should also be part of the design to control drying shrinkage or initial thermal related surface cracking.

9. These vertical face joint notches are usually spaced in the range of 3.7 to 4.9 m. Surface cracks will usually initiate in the face joint and could propagate downstream later. The face joint notches should be either waterstopped or sealed. At times these will require resealing

10. Crack inducers need not be placed in every lift in the full upstream downstream direction to be effective. Placing the crack inducer in every other lift seems to work effectively. Extending the inducer only a partial distance from both the upstream and downstream faces is not recommended, as it has been found the upstream – downstream propagation of the cracks do not actually meet up, with the result that the downstream initiated one is not sealed by a waterstop. Salto Caxias dam is a good example of this.

11. An old graph showing typical adiabatic heat rise curves for up to 28 days for

varying Type I and II Portland cements should not be used. This is because newer cements produce more early heat than in the past due to finer grinding and the use of fly ash in the mixture produces a heat peak well past 28 days. This increased temperature peak may be offset by a heat loss to the atmosphere and other boundary conditions greater than the 25% assumed by some designers.

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