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# CONTRACTION JOINTS AND MONOLITHIC BEHAVIOR OF RCC ARCH DAMS

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## ABSTRACT

All arch dams, whether constructed of Conventional Concrete (CVC) or Roller Compacted Concrete (RCC) are three dimensional structures, elastically deforming in all directions and planes when responding to external and internal loads and forces. Both types of arch dams are constructed in horizontal lifts and radial contraction joints are formed or cut to prevent cracking. If the lift joints and the contraction joints are not properly treated, adequate elastic response and monolithic action may not be obtained. This paper analyzes two design and construction measures that could be adopted to ensure elastic monolithicity of a RCC arch dam.

## STRUCTURAL CONCEPT OF ARCH DAMS

All arch dams, whether constructed of **C**onventional **V**ibrated **C**oncrete (CVC) or **R**oller **C**ompacted **C**oncrete (RCC) have one common structural feature: curvature. Ideally, for optimum elastic response the arch dam must be elastically monolithic in all directions. Since both CVC and RCC dams are constructed in horizontal layers or lifts, to achieve monolithic behavior there should be adequate bond at horizontal construction joints. Similarly, if vertical radial contraction joints are provided, there should be a high degree of effective monolithic action, that is, bond, flexural and shear strengths, at the joint.

## SHAPE AND THICKNESS

The geometry of the curvature and thickness of the dam, both horizontally and vertically, depend on:

- Height of the dam;
- Shape of the dam site;
- Strength of the concrete;

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- Permissible maximum compressive, tensile and shear stresses;
- Loading criteria, including seismic factors;
- Thermal properties of the concrete and cyclical ambient temperatures;
- Strength or modulus of elasticity of the foundations and abutments;
- Degree of constraint at the dam-foundation contact;
- Type and treatment of radial contraction joints.

Thicker arch dams are sometimes called gravity arch or arch gravity dams. These terms are misnomers, because gravity action between horizontal arches, to varying degree, is always a factor in structural behavior of all arch dams. RCC arch dams are generally thicker than comparable CVC dams because of the relatively low design strength of their concrete.

## CONTRACTION JOINTS: NEED AND SPACING

Contraction joints in unreinforced concrete are provided mainly to eliminate the risk of cracking in the body of the dam. The principal cause of such cracking is the contraction and tensile strains caused by drop in body temperature of the dam from its peak to the ultimate stable range. The rise, the amount and rate of drop of concrete temperature depends on several factors, namely:

- Cementitious (cement plus pozzolanic material) content of the concrete;
- Adiabatic temperature rise;
- Placing temperature of CVC or RCC;
- Exposure to solar radiation, particularly of RCC;
- Average annual and seasonal ambient temperature;
- Temperature of reservoir water;
- Volume of concrete and width, length and thickness of the dam;
- Diffusivity and rate of cooling of the concrete mass or rate of temperature drop ($^{o}$C per day);
- Degree of restraint to contraction of concrete, particularly near foundations.

Of the above, cementitious content is the most influential factor. It can be appreciably lower in RCC than for comparable CVC, consequently, RCC has lower heat of hydration and peak body temperatures than CVC. Rapid placement of RCC reduces the amount of cooling by air convection during the early stages. On the other hand exposure of large areas of RCC to solar radiation and high ambient temperatures increase the peaks.

Temperature histories for typical RCC and CVC mixes with comparable design strength are shown in Figure 01. Characteristics of the mixes are shown in Table 01. The induced tensile stresses indicate that the risk of cracking in CVC with Mix (B) is about 50 percent greater than in RCC with Mix (A), and to prevent structural cracking the typical spacing of transverse (radial) contraction joint in the CVC dam would be 15 to 20 m and in the RCC dam about 20 to 30 m.

In optimizing the design of an arch dam, whether RCC or CVC, an important objective is to reduce the volume of concrete by using higher strength concrete, that is, with higher cementitious content. Consequently, for temperature control, to prevent cracking, and to ensure monolithic behavior, closer spacing of contraction joints, lower placement temperature, postcooling of concrete, and grouting of the contraction joints would be necessary.

| | **Unit** | RCC Mix (A) | CVC Mix (B) |
|---|---|---|---|
| Cement Content | kg/m$^3$ | 120 | 150 |
| Pozzolanic Material Content | kg/m$^3$ | 40 | 40 |
| Maximum Size Aggregate (MSA) | mm | 75 | 150 |
| Adiabatic Temperature Rise (dam body) | $^o$C | 12 | 20 |
| Concrete Placing Temperature | $^o$C | 10 | 10 |
| Average Annual Ambient Temperature | $^o$C | 20 | 20 |
| Maximum Temperature Drop | $^o$C | 15 | 20 |
| Rate of Cooling | $^o$C/ day | 0.5 | 0.5 |
| Maximum Tensile Stress due to Cooling, at Foundation | MPa | 1.5 | 2.5 |

Table 01- Typical RCC & CVC Mixes for same strength level

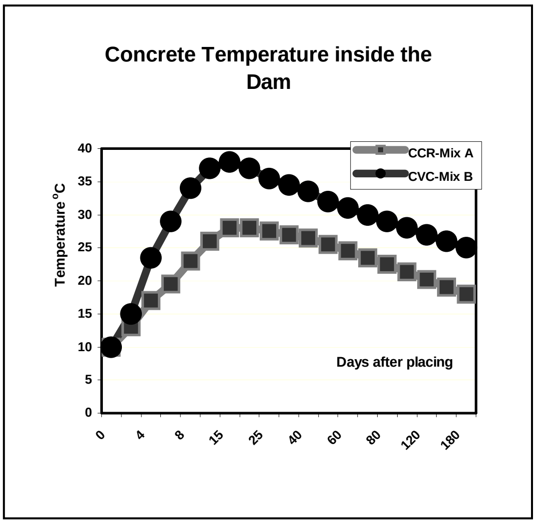



Figure 01- Temperature Histories for Typical RCC and CVC, for same strength levels

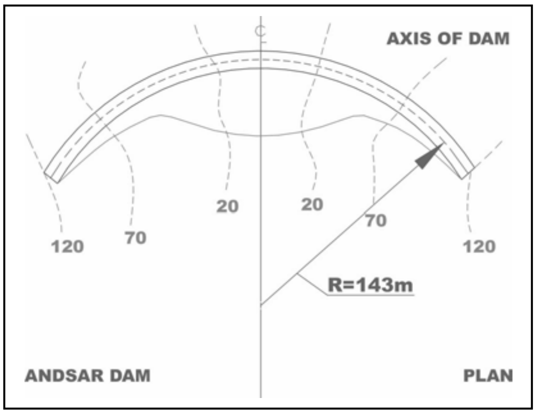
## TREATMENT OF CONTRACTION JOINTS IN RCC DAMS

Postcooling of concrete and grouting of transverse contraction joints are major disadvantages for a RCC arch dam, because they would slow down construction and increase costs. This would be a particularly serious consideration for higher, longer and larger RCC arch dam.

Postcooling of RCC, in order to sufficiently open the contraction joints, including refrigeration plant, embedded tubing, pumps and valves can add US$ 3 per cubic meter to US$ 5 per cubic meter or more, that is 10 to 15 percent of unit cost of RCC without postcooling. For large RCC arch dam with a volume of 1,000,000 m$^3$, the increase in cost can be as high as US$ 5milion, without adding the cost of delays. Therefore, it is very important to analyze alternatives for reducing such costs without adversely affecting the quality and monolithic behavior of a RCC arch dam. The following design and construction measures for achieving the quadruple objectives of reducing the number of contraction joints, ensuring monolithic performance, elimination of post-cooling and reducing costs are discussed in this article:

- Precooling of aggregates and lower RCC placement temperatures;
- Grouting of contraction joints by gravity in stages;
- **P**ressure **C**ompensating **C**hambers (PCC) in contraction joints.

The methodology recently adopted by Chineses using cement composition with a specified MgO content to assure a controled expansion, will not be discussed in this paper. The example of **Andsar Dam**, a 120 m high, 300 m crest length RCC arch dam that is under study, is used to illustrate the feasibility of the above measures. It is located in a symmetrical "V" shaped site, in a sub-tropical zone, with a volume of 450,000 m3. Its plan and sections are shown in **Figure 02**. Average ambient temperature at the dam site have the following seasonal values: summer: 30$^{o}$C, winter: 10$^{o}$C, average: 20$^{o}$C. The RCC Mix (A) and placing temperatures shown in **Table 01** were assumed, for the study.



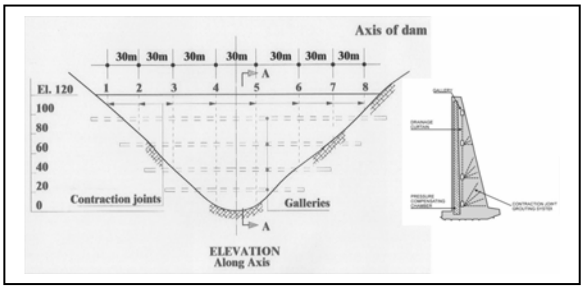




Figure 02- Andsar RCC Arch Dam – Plan

Figure 03- Andsar Dam- Contraction Joints and Grouting

The maximum principal stresses in the upstream and downstream faces would be in the following ranges:

| Stress | Upstream Face | Downstream Face |
|---|---|---|
| Compressive (MPa) | 6.0 – 8.0 | 5.0 – 7.0 |
| Tensile (MPa) | 1.0 – 1.2 | 0.5 – 0.7 |

Cooling of concrete from the peak to the average annual or stable temperature of 20$^{o}$C, contributed 0.5 to 1.0 MPa of the tensile stress near the abutments and base of the dam. Typical distribution of horizontal (arch) stresses across the thickness of the dam is shown at locations of radial contraction joints that are spaced at 30 m. The stresses were computed assuming elastic monolithic continuity at the contraction joints. RCC mix specifications and other criteria were assumed as follows:

| | |
|---|---|
| Cement Content | 120 kg/m$^3$ |
| Pozzolanic Material Content | 40 kg/m$^3$ |
| RCC Placing Temperature | 10 $^o$C |
| Peak Temperature | 30 $^o$C |
| RCC layer thickness | 30 cm |
| Maximum Size Aggregate (MSA) | 75 mm |
| Minimum RCC Required Strength @ 90 days | 20 MPa |

Applicability of the three design and construction concepts of **Andsar RCC Arch Dam** are evaluated in this paper.

## LOWER PLACING TEMPERATURES

The peak temperature of concrete is affected by: cementitious content of the mix, the rate of placement, the thickness of the layer, the ambient temperature and the placing temperature. All other factors being equal, the higher the placing temperature, the higher will be the peak temperature in the concrete mass and greater the drop to the ultimate stable temperature, and consequently higher the tensile strains. Precooling of aggregates, using ice to replace the mix water, would be necessary to obtain a concrete placing temperature 5$^o$C to 10$^o$C below the average seasonal ambient temperature. From experience at various projects it is estimated that for a 500,000m$^3$ dam, precooling cost (equipment +operational +maintenance) would be about US$ 1.0 to 1.3 per degree of precooling, per cubic meter of concrete.

The advantages of lower placing temperatures are: fewer contraction joints, lesser amount of joint grouting and without postcooling. One degree of precooling corresponds to a reduction of about 0.12 MPa in tensile stress near the area of maximum constraint. The reduction of 1.0 MPa in tensile stress due to cooling corresponds to an increase of about 5m in spacing of contraction joints. For **Andsar Dam,** data for placing temperatures of 12 $^o$C and 9 $^o$C are compared below.

| Placing Temperature ($^o$C) | 9 | 12 |
|---|---|---|
| Total area of contraction joints (m$^2$) | 7650 | 9000 |
| Cost of cutting and grouting joints (US$) | 200,000 | 250,000 |
| Cost of preecoling (US$) | 7,200,000 | 5,850,000 |
| Joint cost saving (US$) | 50,000 | |
| Extra cost of precooling (US$) | 1,350,000 | |
| Extra cost for postcooling (US$) | | 1,800,000 |
| No postcooling savings (%) | 28% | |

The lowest placing temperatures would be most beneficial in areas of high constraint where the cracking potential would be the highest. For **Andsar Dam** the highest risk of cracking would be at the upstream face along the sloping abutments and at the base of the highest portions of the dam. Such a critical zone for **Andsar Dam** would be about 15 m thick along the entire foundation.

## GROUTING CONTRACTION JOINTS BY GRAVITY

Pacoima arch Dam in California, USA, was built of CVC in 1929. It is 112 m high with a crest length of 180 m and volume of 170,000 $m^3$. It has 11 contraction joints with interlocking vertical keys. No postcooling was provided and the contraction joints were grouted by gravity from the top of the dam through embedded vertical pipes. The dam was shaken by severe earthquakes of *Richter M 6.6* and *M 6.8*, in 1971 and 1994, respectively; but the dam performed essentially monolithically without permanent differential displacements at the contraction joints.

Contraction joints in the **Andsar Dam** would be grouted from horizontal galleries located in the dam, from El. 20 to El.100 and from the crest of the dam, after the entire dam is completed and the reservoir is still empty. As shown in **Figure 03**, the eight contraction joints are spaced 30 m and access to the galleries at El. 20 and El. 70 that extends into both abutments, would be from the downstream side. For grouting the contraction joints, 75 mm diameter, 1.0 m long metal pipe stubs would be embedded in and along the alignment of the joints, in the floor and downstream wall of the gallery. The number of grout pipes would depend on the width of the joint to be covered. Length of each grout hole would be about 3m short of the downstream face of the dam. In cut or partially induced contraction joints upstream waterstops would be provide but none near the downstream face. If there is excessive loss of grout, epoxy putty can be used to seal the downstream end of the joint.

Joint grouting would commence from the lowest gallery; this first stage would cover portions of joints 4 and 5, below El. 20. From the other galleries, grout holes would be mostly downward and cover areas of other joints. The upper 20 m of all joints would be grouted from the top of the dam through three or four holes drilled into joints. Prior to grouting, water loss test under very low pressures would be made to estimate joint opening. If the joint opening averages less than 0.5 mm, ultrafine cement grout may have to be used. In any case, all joint grouting would be under very low pressures; that is essentially by gravity.

## PRESSURE COMPENSATING CHAMBERS IN CONTRACTION JOINTS

The use of **P**ressure **C**ompensating **C**hamber (PCC) has been adopted since 1970 in some large concrete dams in Brazil; for example: Ilha Solteira power intake, Itaipu hollow gravity dams blocks and Ita water intake. The beneficial effects of the PCC are best illustrated by its incorporation in the design of the Itaipu hollow gravity dam. The blocks have a width of 34 m and maximum height of 196 m; both unprecedented for this type of dam. The minimum thickness of concrete at the crown of the upstream head is only 16 m under maximum reservoir pressure. Mathematical analyses indicated that there was a serious risk of transverse cracking if there was a rapid drop of $5^oC$ to $10^oC$ in concrete temperature, combined with a lateral temperature gradient from the massive interior to the slender part of the head.

Provisions of postcooling of concrete or steel reinforcement were not considered because of the high additional costs. Instead the PCC concept was adopted in two ways: (1) the upstream waterstop was located 7.5 m to 10.0 m downstream of the upstream face of the contraction joint; (2) a 5.2 m wide PCC confined between two waterstops was located downstream of the joint drain. **Figure 04** shows the two types of PCCs that were used in Itaipu dam; and are discussed bellow.

Two types of a Pressure Compensating Chamber (PCC) at the upstream end of a contraction joint in a RCC arch dam are shown in **Figure 05**. In Type I PCC is a part of the contraction joint and is open to the reservoir; it is not confined between waterstops, and pressure in the chamber would fluctuate with reservoir level. In Type II, the PCC is confined between two waterstops and is filled with water either from the top of the dam or through a filling line connected to the reservoir and controlled by valves in the galleries. A drain into the galleries, with valves, would be used to fully or partially drain the PCC. Thus the pressure in a Type II PCC can be adjusted.

Since transverse cracks due to cooling of RCC are likely to commence before reservoir filling can begin, for an RCC arch dam it would be preferable to use Type II PCC and pressurize them by filling them with pumped water. Pressure in the PCC would further open the contraction joints and partially reduce the tensions due to cooling of the mass concrete between the contraction joints. If considered beneficial, the Type II PCC can be injected with an expansive grout either before or, if considered permissible after partial filling of the reservoir.

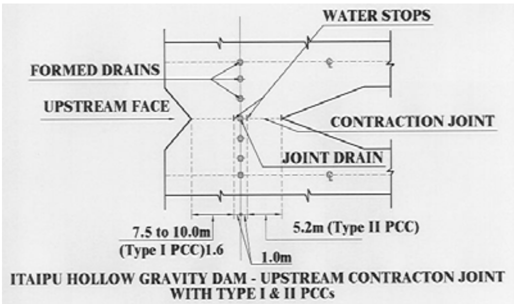



Figure 04- Itaipu Hollow Gravity Dam – Upstream Contraction Joint With Type I & II PCCs.

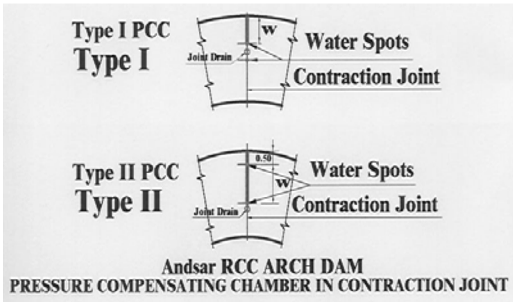



Figure 05- Andsar Dam- Location of the Two Types of PCC

While the effectiveness of a PCC in improving the stability of individual gravity dam blocks has been well demonstrated at Itaipu and other Brazilian dams, could the PCC also be beneficially employed in three-dimensional monolithic RCC arch dams?
To evaluate the effect of the two types of PCC on horizontal arch stresses, two-dimensional mathematical models were analyzed by the finite element method. Arches at El. 30 and 80 were considered representative, and analyzed for three conditions:

- **Case 1:** Monolithic arch; contraction joints grouted; modulus of elasticity of concrete= modulus of the abutment rock = 25,000 MPa. Reservoir full. No temperature effects considered;
- **Case 2:** Same as for Case 1, but with Type I PCC pressurized by reservoir filling;

- **Case 3:** Same as for Case 1, but with Type II PCC pressurized before filling of reservoir.

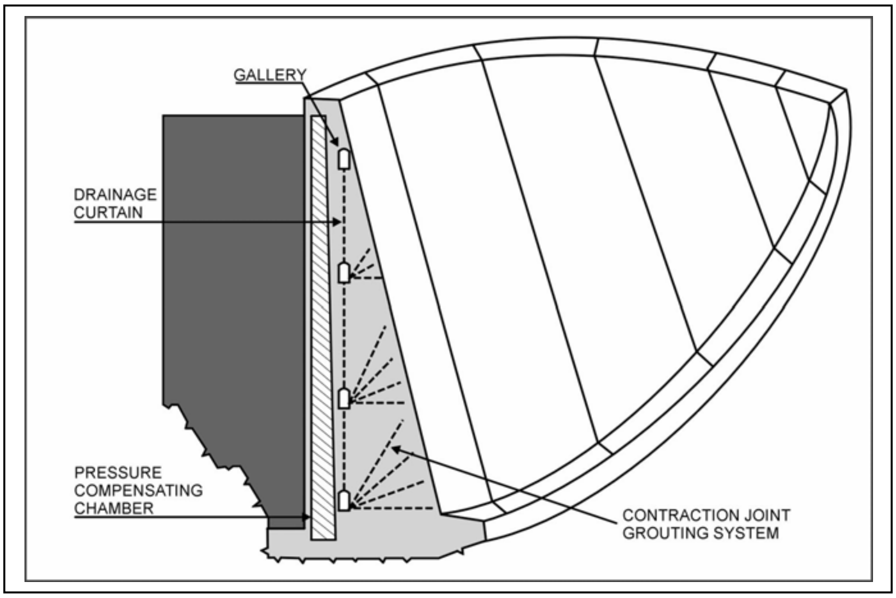



Figure 06- Andsar RCC Arch Dam- Galleries & PCC- Cross Section

## EFFECT OF THE PCC ON ARCH STRESSES

The results of the analyses, that is the distribution of horizontal arch stresses at El. 30 and 80 are graphically presented in **Figures 07** to **13**, and discussed below.

**Case 1: Monolithic Arch- (Figures 07 and 08).**

Stresses at both faces are mostly compressive and range from 5.5 MPa to 0.4 MPa. Tensile stresses of about 0.9 MPa occur on the upstream face near the abutments over very small areas. At El. 30 both maximum compressive and tensile stresses are within the allowable limits for the design RCC mix, with somewhat higher cementitious content in the upstream areas of potential tensions. These stress results also illustrate the need to eliminate structural cracks and obtain a high degree of monolithic elastic behavior of the dam by grouting the contraction joints.

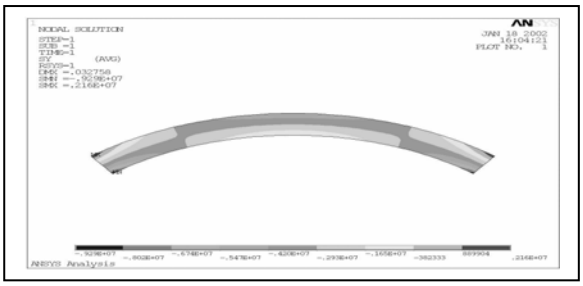


Figure 07- Andsar Dam- Arch Stresses at El. 80- Case 1

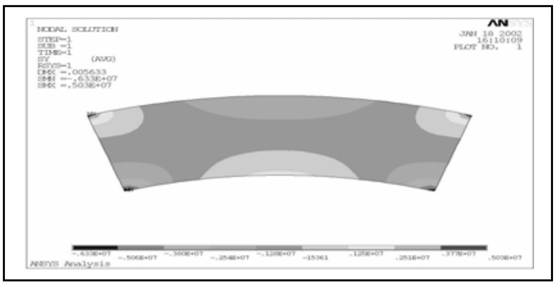


Figure 08- Andsar Dam- Arch Stresses at El. 30- Case 1

**Case 2: Contraction Joints with Type I PCC- (Figures 09, 10 and 11).**

The contraction joints are spaced at 30 m and the PCC width from the upstream face is equal to 0.33 of the thickness of the arch. Comparing the stress distributions at El. 80 for the monolithic condition (**Figure 07**) against that for Case 2 (**Figure 09**), it is seen that the introduction of Type I PCCs, increased the tensile stress in the upstream face near the abutments to about 1.5 MPa over an area about two times larger than for Case 1. Maximum compressive stresses near the downstream end of the PCC would be about 7,5 MPa and some tensile stress concentrations would occur at its terminus. The arch at El. 30, considering its short span and thickness, essentially acts like a deep girder. Also, the vertical "cantilever" effect would be accentuated and the vertical tensile stresses at the upstream face would be higher than the horizontal arch stresses. Comparing the arch stresses for monolithic condition Case 1 (**Figure 08**), it is seen that the introduction of Type I PCC had only a small effect on the magnitude and distribution of compressive stresses.

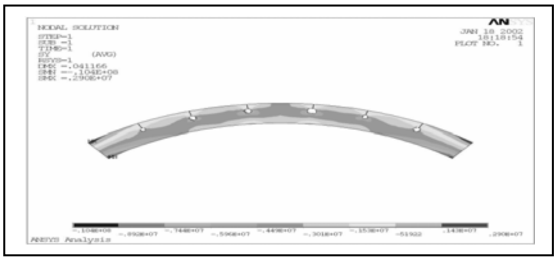


Figure 09- Andsar Dam- Arch Stresses at El. 80- Case 2

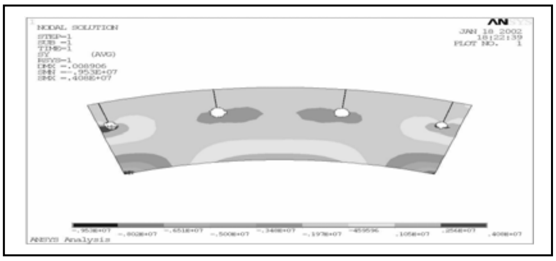


Figure 10- Andsar Dam- Arch Stresses at El. 30- Case 2

**Case 3: Contraction Joints With Type II PCC- (Figures 12 and 13).**

Type II PCC with a width equal to 0.25 of the thickness of the arch, were assumed at the same location as for Case 2. The upstream end of the PCC was located 0.5 m from the upstream face. The PCCs were pressurized to full reservoir pressure and the contraction joints grouted, before filling of the reservoir. The PCCs themselves were not grouted. The arch stresses at El. 80 and El. 30 are presented in **Figures 12** and **13**, respectively. At El. 30 the arch is almost entirely in compression; very low tensile or compressive stresses are indicated in the upstream face. Comparing **Figures 12** and **07**, it appears that for Case 3 with Type II PCCs, the stress distribution is better than that for the monolithic condition, in that the tensions in the upstream face are greatly reduced or eliminated. At El. 30, the arch is essentially in compression, with some tensile stress concentrations near the downstream end of the PCC.

## PREFERABLE TYPE OF PCC

For an RCC arch dam, the Type II PCC is preferable over Type I because of the following factors:

▪ Type II PCCs can be pressurized, the contraction joints sufficiently opened and grouted to restore monolithic conditions, before filling of the reservoir. Similarly, it can be dewatered, if necessary, even when the reservoir is full;

▪ In colder climates, penetration of very cold water into a Type I PCC could induce tensile stresses and cracking, and increase undesirable saturation of concrete in the upstream part of the dam;

▪ A Type I PCC would considerably reduce the elastic continuity of the arch and the three-dimensional monolithicity of the entire dam. An undesirable consequence would be substantial increase in vertical and principal tensile stresses along the base and abutments at the upstream face of the dam. Before finalizing the design and construction details of a PCC, several factors that would affect costs and the construction schedule, need to be analyzed. Among these are: formwork for the PCC, type and installation of the waterstops and the timing and need for grouting the PCC.

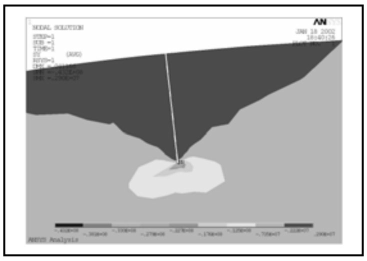


Figure 11- Andsar Dam-Arch Stresses at El. 80-Case 2

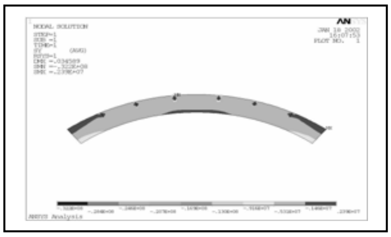


Figure 12- Andsar Dam-Arch Stresses at El. 80-Case 3

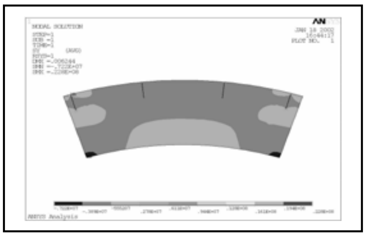


Figure 13- Andsar Dam-Arch Stresses at El. 30-Case 3

## CONCLUSIONS

To construct economic RCC arch dams to standards of quality, safety, durability and structural performance equivalent to that for a comparable CVC arch dam, it is necessary to reduce their costs and time required for completion. Three major factors that increase costs are: the number of radial contraction joints, postcooling of concrete required prior to grouting of the joints and delays in filling the reservoir. Two design and construction measures are discussed in this paper, which in combination, or separately, could attain the above objectives. These are: precooling of aggregate and lower placement temperature of RCC and use of PCCs in the contraction joints. The Type II PCC is preferable because it is independent of the reservoir, and the contraction joints can be grouted before filling the reservoir. Pressurizing the PCC also improves the stress distribution with only minor tensions around the chamber itself. If after some years of service, it is considered necessary, the PCC can be filled with expansive grout and sealed permanently to improve monolithic behavior of the dam.

In order to optimize the design and construction details and determine realistic costs, it would be necessary to make three-dimensional stress and stability analyses, with and without the PCC, and in combination with a range of concrete placement temperatures.