CHAPTER 3

3.   LITERATURE AND REFERENCE:

THE TRADITIONAL APPROACH TO DAM DESIGN IN RESPECT OF EARLY CONCRETE BEHAVIOUR AND TEMPERATURE LOADS AND THE ASSOCIATED APPLICATION FOR RCC DAMS

3.1.   INTRODUCTION

On the basis of referenced literature, the state of the art in respect of typical design approaches and RCC behaviour in dams, with particular reference to early shrinkage and creep, is presented in Chapter 3.

The literature review is presented in four distinct parts. The first part addresses the accepted approach with which shrinkage and creep are accommodated in CVC dam design and quotes guidelines and other references that have applied the same approach for RCC dams. The second part addresses earlier investigations and laboratory testing that suggest that shrinkage and creep in RCC are similar to that typically expected in CVC. The third part presents notional evidence that supports a view of reduced shrinkage and creep in RCC compared to CVC. The fourth part addresses the characteristics of concrete that increase susceptibility to shrinkage and creep and presents a review of the properties of lean and high-paste RCC in relation to these characteristics.

3.2.   BACKGROUND

In setting the scene for the studies undertaken as part of this investigation, it is considered of value to describe the state of the art understanding and practice in respect of managing the early behaviour of concrete and RCC in large dams. In order to promote a better understanding of the need for the work addressed herein, it is considered beneficial to define the early heat development and dissipation processes that impact mass concrete, to discuss how these are managed in conventional mass concrete and to illustrate how the related problems are more complex in the case of Roller Compacted Concrete.

Dam engineering technology applies temperature drop loads to make provision for early concrete shrinkage and creep effects and a particular effort will be made to describe the actual behaviour for which simplified assumptions are made in design.

It is considered particularly relevant to note that 28 of the 118 papers included in the proceedings of the 5th International Symposium on RCC (titled New Progress on RCC Dams) held in Guiyang, China in November 2007, directly addressed the issue

of temperature in RCC dams. This can be compared with 9 out of the submitted 154 papers of the 4th International Symposium on RCC held in Madrid in 2003, indicating the increasing perceived importance of thermal impacts on RCC dams. Also of interest is the fact that while only 4 papers addressed RCC arch dams in 2003, that number increased to 10 in 2007.

PART I: DESIGN FOR EARLY THERMAL EFFECTS IN CVC DAMS

3.3. EARLY CONCRETE BEHAVIOUR IN LARGE DAMS

3.3.1. LITERATURE

The issues of autogenous and drying shrinkage and stress relaxation creep are not specifically addressed in dam design literature, with the consequential shrinkage rather treated as a thermal contraction. The ever-increasing trend towards the almost exclusive use of RCC for the construction of concrete-type dams has, however, resulted in a growing focus on prediction of the early thermal behaviour, as derived through analysis.

The United States Army Corps of Engineers (USACE) has published three guidelines that address the necessary analysis of the early thermal behaviour of RCC dams and the appropriate approach to dam design for long-term temperature loads; *Thermal Studies of Mass Concrete Structures.* 1997[1], *Roller Compacted Concrete.* 2000[2] and *Gravity Dam Design.* 1995[3]. In addition, the USACE's Engineering Manual *Arch Dam Design.* 1994[6] addresses the requirements of thermal design for CVC arch dams. The United States Department of the Interior, Bureau of Reclamation (USBR) *Design of Arch Dams.* 1977[5] includes a chapter on Temperature Studies for Dam Design.

The above literature comprised the primary sources of the subsequent discussion on the manner in which early thermal effects and shrinkage and creep behaviour are traditionally addressed in concrete dam design and how this approach has been applied for RCC dam design.

3.3.2. GENERAL

Thermal issues for large-scale concrete pours can be divided into two specific categories[1]; Surface Gradient and Mass Gradient effects. In principle, Surface Gradient effects are relatively short term in duration and are more critical in the case of CVC than RCC, due to the higher hydration heats generally prevalent in the former concrete type. Mass Gradient effects occur later, as the retained hydration heat is slowly dissipated and are more critical in the case of RCC, in which contraction joints must be induced and for which grouting of contraction joints is a more complex issue. In very large mass concrete dams, the hydration heat can take more than 50 years to be fully dissipated from the dam core.

The intensity of the impact of both surface and mass gradient effects is determined by the magnitude of the hydration heat developed, the placement temperatures and the relative extremities of external temperatures. As a short-term issue, surface gradient effects are generally more intense during winter, while mass gradient effects are largely determined by the overall regional climate.

Due to the fact that hydration heat is evolved early during the strength development process, the consequential thermal expansion is generally accompanied by significant levels of creep. External zones from which hydration heat is quickly dissipated experience lower maximum temperatures and consequently less creep and accordingly, a complex stress field is developed across the structure. Early thermal effects in large-scale mass concrete consequently relate to thermal gradients and the differential development of creep across the structure.

Figure 3.1 illustrates the typical short and longer-term stress development patterns as a consequence of hydration heat development and dissipation within a large concrete body.

| **Surface Gradient Effects: Short Term** | **Mass Gradient Effects: Long Term** |
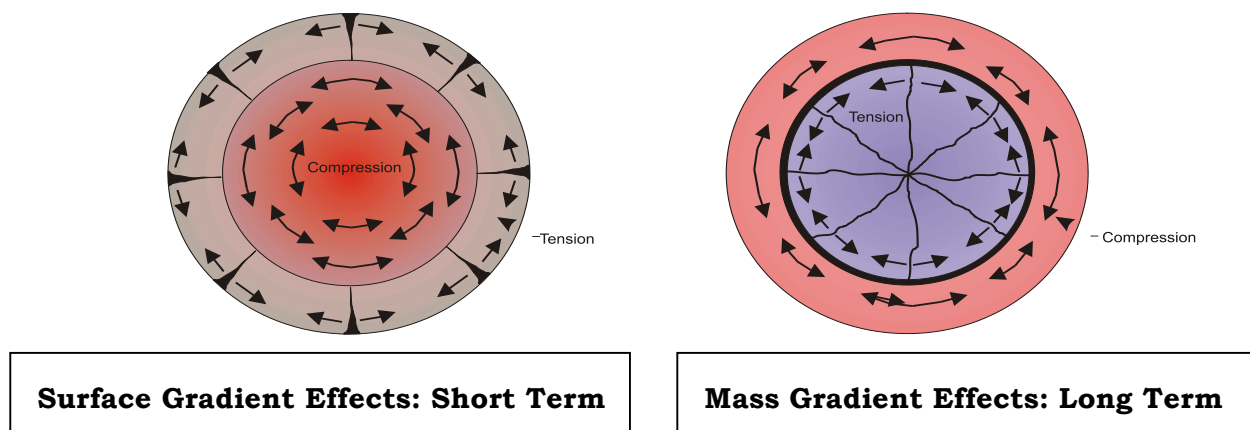
Figure 3.1: Thermal Gradient Stress Development

In a large concrete body, the evolution of hydration heat will cause the body to become significantly warmer than its immediate environment. As the temperature increases, heat will be dissipated relatively rapidly from the surface zone into the cooler external environment and a temperature gradient will develop between the core and the surface of the structure. While in this hot, expanded state, the internal, immature core concrete can experience significant creep, particularly manifested in the form of stress relaxation when thermal expansion is constrained. The surface zones, on the other hand, are never exposed to such high levels of temperature and consequently will not be subjected to the same levels of compressive stress and accordingly, little or no creep is consequently incurred. In this process of heat development and dissipation, two effects are experienced. The first relates to a warmer, expanded core and a cooler surface, which gives rise to core compression and surface tension that can result in cracking. The second

effect occurs later as the core cools and shrinks more than the surface zone as a consequence of the creep experienced and the greater cooling range applicable. This effect results in compression in the surface and tension in the core, potentially giving rise to cracking in the core zone.

The intensities of the surface and mass gradient effects are obviously directly related to the temperature gradients experienced between the core and the surface, during the processes of heating and cooling. The first effect will usually be most pronounced when the internal temperature is at its highest and accordingly the related consequences are usually experienced during the construction period. The second effect will occur later, as the body of the dam cools. As a consequence of the immaturity of the concrete at the time that the highest core temperatures are experienced in a large concrete dam wall, creep will partly mitigate the impact of surface gradient effects. As a consequence of a significantly greater concrete maturity at the later time of occurrence of the mass gradient effects, less creep will occur in mitigation and a higher susceptibility to cracking is developed.

To provide some perspective to any quantitative analysis in respect of the above effects, it is interesting to quote the USBR's *Design of Arch Dams.* 1994[6] as follows:

> *Unlike ordinary structural members undergoing temperature change, the stresses induced in mass concrete structures by temperature changes are not capable of being defined with any high degree of accuracy. The indeterminate degree of restraint and the varying elastic and inelastic properties of the concrete, particularly during the early age of the concrete, make such an evaluation an estimate at best.*

3.3.3.   MANAGING EARLY THERMAL GRADIENT EFFECTS IN CVC

While higher cement contents give rise to greater total hydration heat development in the case of CVC, various factors make management of the consequential problems more straightforward than is the case for RCC. Construction in vertical monolithic blocks of limited size (see **Plate 3.1**) and separated from each other with contraction joints, the use of ice and chilled water in the mix and the circulation of cooling water through the placed concrete serve to minimise the thermal tension stresses developed[1]. With higher water contents in CVC than RCC, replacement of water with ice in the mix is more effective in reducing the maximum concrete temperature experienced during hydration, while the circulation of chilled water through steel pipe loops in CVC is effective in drawing out heat and reducing the maximum temperatures experienced in the core zone.

A general rule of thumb[1] for mass concrete suggests maximum internal/external concrete zone temperature differences of 20℃ to prevent surface cracking and 15℃ to prevent internal cracking.
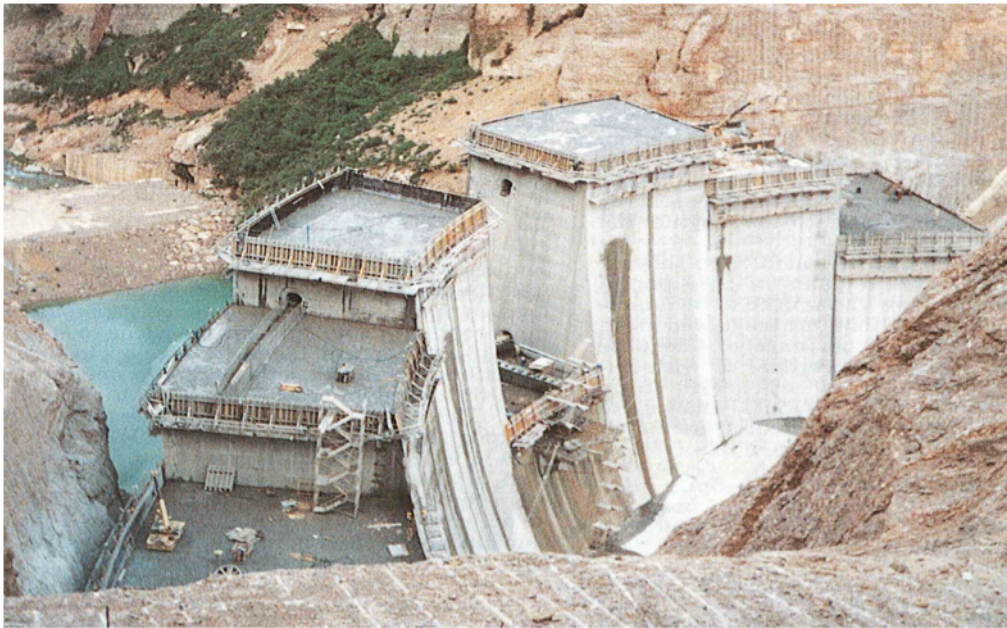
Plate 3.1: CVC Dam Construction in Vertical Monoliths

3.3.4.   MANAGING EARLY THERMAL GRADIENT EFFECTS IN RCC

While the author has no knowledge of internal core cracking in RCC having yet been caused by short-term temperature gradient effects, numerous examples exist where surface cracking has been developed. Furthermore, although the total hydration heat development in RCC is typically lower than is the case for CVC, the reduced water content implies that ice is less effective in restricting the maximum temperatures experienced, while the inclusion of cooling pipes is of significantly greater impact on the construction process and realistically impractical.

The management of early thermal gradient effects in large RCC dam construction has to date consequently been achieved primarily by limiting the maximum temperature experienced within the core zone. For typical RCC adiabatic hydration temperature rises of 10 to 18℃, limiting thermal gradients from core to surface to approximately 20℃ is relatively straightforward.

In the case of high-workability RCC, the maximum hydration temperature rise can exceed 20℃ and pre-cooling of the RCC is consequently usually required in order to maintain acceptable thermal gradients.

In a temperate climate, sensible control of the temperature of each of the constituent materials and sometimes avoiding placement during the warmer parts of the summer season are usually quite adequate to avoid the development of dangerous thermal gradients. In less temperate climates, the use of chilled water and ice is usually required, together with wet-belt cooling of the coarse aggregates,

while in more extreme climates, seasonally restricted placement will be enforced in tandem with an appropriate combination of the previously mentioned measures augmented with others, such as fogging of the placement area.

3.4. INTERMEDIATE THERMAL EFFECTS IN LARGE MASS CONCRETE DAMS

3.4.1. GENERAL

Notwithstanding the importance of the surface gradient thermal effects, it is, however, the longer term cooling of the internal zone of the dam wall that is of most interest in respect of the structural action of an arch dam and in respect of the potential development of cracking parallel to the axis in a large gravity dam. The applicable long-term temperature drop is the difference between the "zero thermal stress temperature" experienced during the hydration cycle and the final equilibrium core temperature, experienced once all of the hydration heat has been dissipated. The consequential thermal shrinkage is accommodated parallel to the axis in RCC dams through the provision of transverse induced joints and perpendicular to the axis by limiting tensile stress through placement temperature restrictions.

Referring to **Figure 3.2** below to illustrate the longer term temperature history typical at the core of a large RCC dam, it can be seen that the maximum macro effects of hydration heat dissipation are only likely to be at their worst long after construction completion.
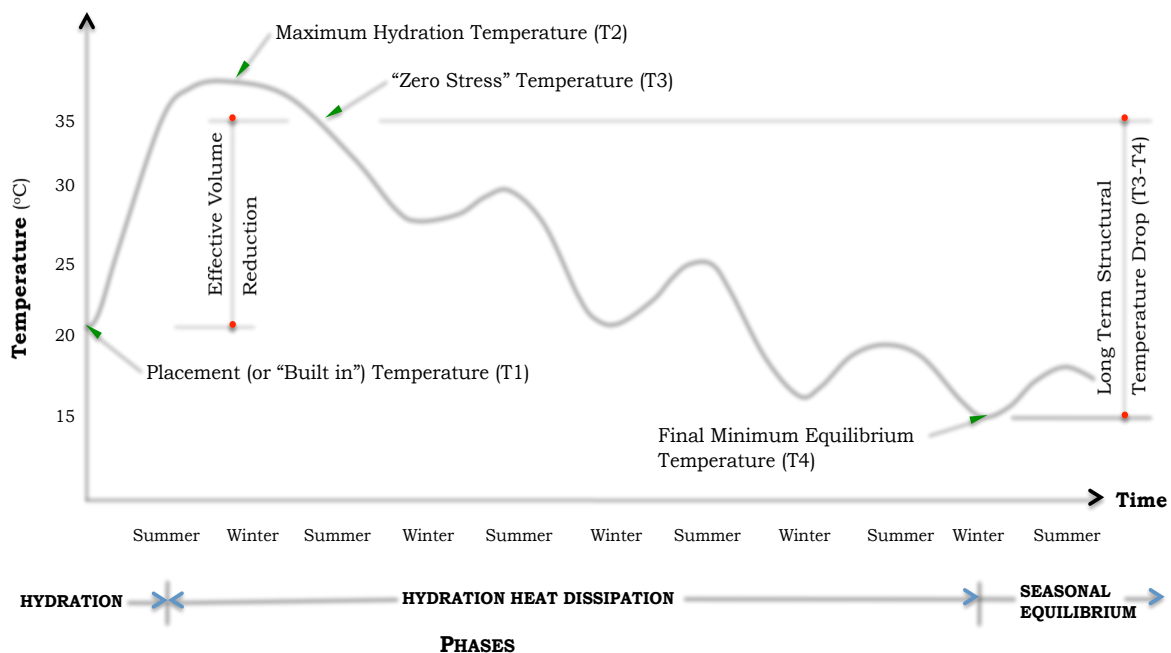
Figure 3.2: Typical Long-term Thermal History

While the maximum temperature within the RCC is generally experienced within a month of placement, the minimum temperatures that determine the maximum temperature drop load will only be experienced during a particularly cold winter after the hydration heat has fully dissipated. In the case of a very large dam, this could be 50 years after completion.

The critical long-term structural temperature drop can accordingly be defined as the difference between the "zero stress" temperature and the lowest temperature experienced once the hydration heat has fully dissipated, towards the end of a particularly cold winter. With the dam wall stress state and volume effectively at equilibrium at the "zero stress" temperature, the restrained shrinkage that will occur with reducing temperature will develop tensions that will give rise to cracking where the concrete tensile strength is exceeded.

In accordance with the indicated design approach, the effective volume reduction in the concrete associated with autogenous and drying shrinkage and stress relaxation creep is correspondingly equated to a thermal contraction consequential to a temperature drop equivalent to the difference between the "Zero Stress" Temperature and the Placement (or "Built in") Temperature.
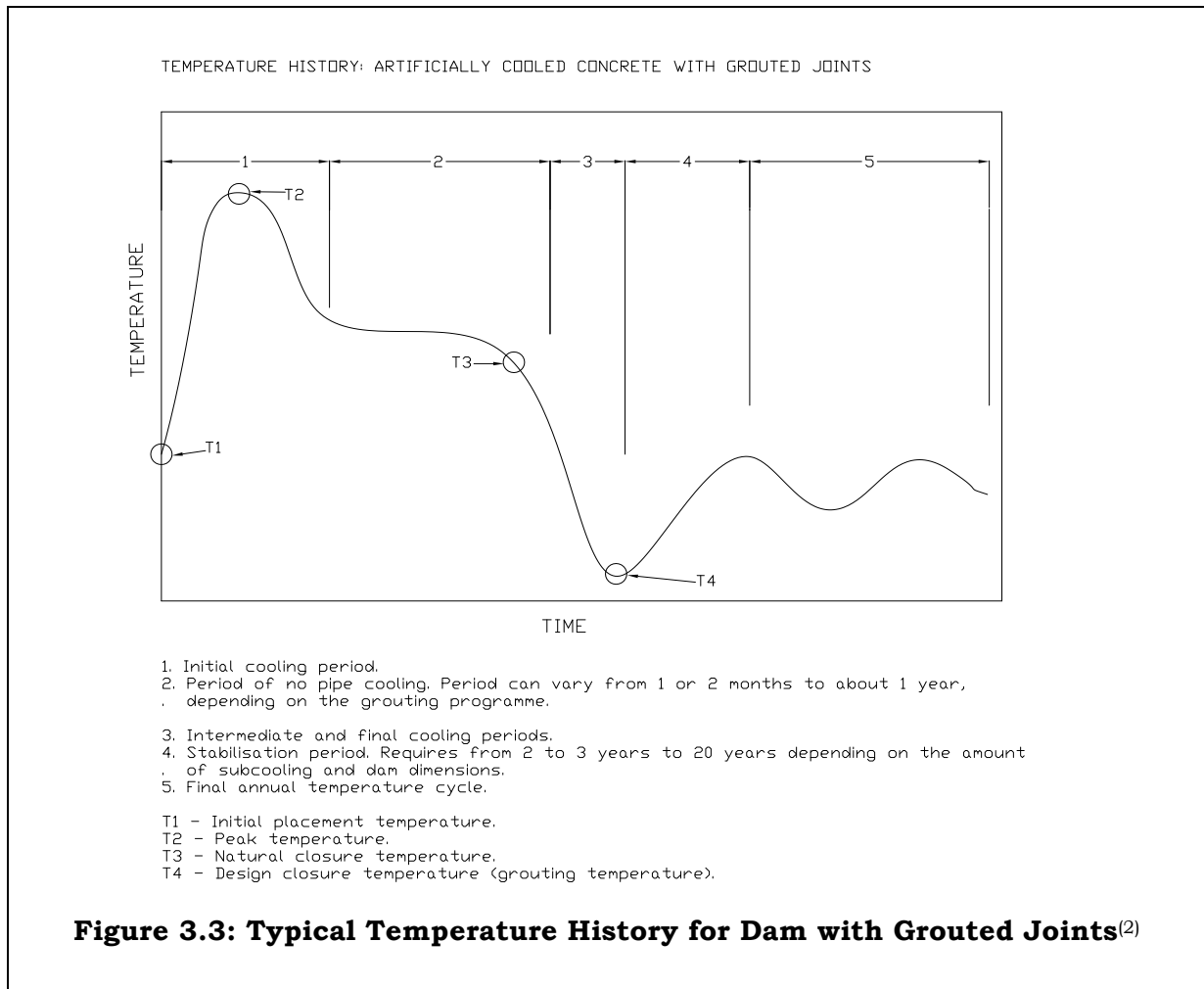
3.5.   DEFINING THE LONG-TERM TEMPERATURE DROP LOAD

3.5.1.   TRADITIONALLY ACCEPTED APPROACH

In relating the applicable early structural temperature loadings, the USACE Engineering Manual on *Arch Dam Design* (EM 1110-2-2201)[4] defines a series of key temperature values, T1 to T4, on a temperature history for artificially cooled concrete, as indicated on **Figure 3.3**.

T1 represents the initial placement temperature, T2 the peak temperature experienced as a result of hydration, T3 the natural closure temperature and T4 the design closure temperature, or the contraction joint grouting temperature. Direct comparisons can be made between the temperatures represented by T1, T2 and T4 and those indicated on **Figure 3.2**; T1 being equivalent to the "built in" temperature, T2 being the peak hydration temperature and T4, the final minimum equilibrium temperature. T3, the "zero stress" temperature, is more difficult to define and will depend on the extent of shrinkage and creep that occurred in the green concrete during the heating and cooling cycle.

While T4 represents an artificially cooled temperature, the typical approach is to set the T4 temperature close to the long-term minimum anticipated temperature. If T4 is below the long-term minimum temperature, temperature drop loading on the dam will never be experienced, but arch compressions will be increased during warmer periods. If T4 is above the long-term minimum temperature, the structure needs to be designed for an equivalent temperature drop.

TEMPERATURE HISTORY: ARTIFICIALLY COOLED CONCRETE WITH GROUTED JOINTS

1. Initial cooling period.
2. Period of no pipe cooling. Period can vary from 1 or 2 months to about 1 year,
. depending on the grouting programme.

3. Intermediate and final cooling periods.
4. Stabilisation period. Requires from 2 to 3 years to 20 years depending on the amount
. of subcooling and dam dimensions.
5. Final annual temperature cycle.

T1 – Initial placement temperature.
T2 – Peak temperature.
T3 – Natural closure temperature.
T4 – Design closure temperature (grouting temperature).

Figure 3.3: Typical Temperature History for Dam with Grouted Joints[2]
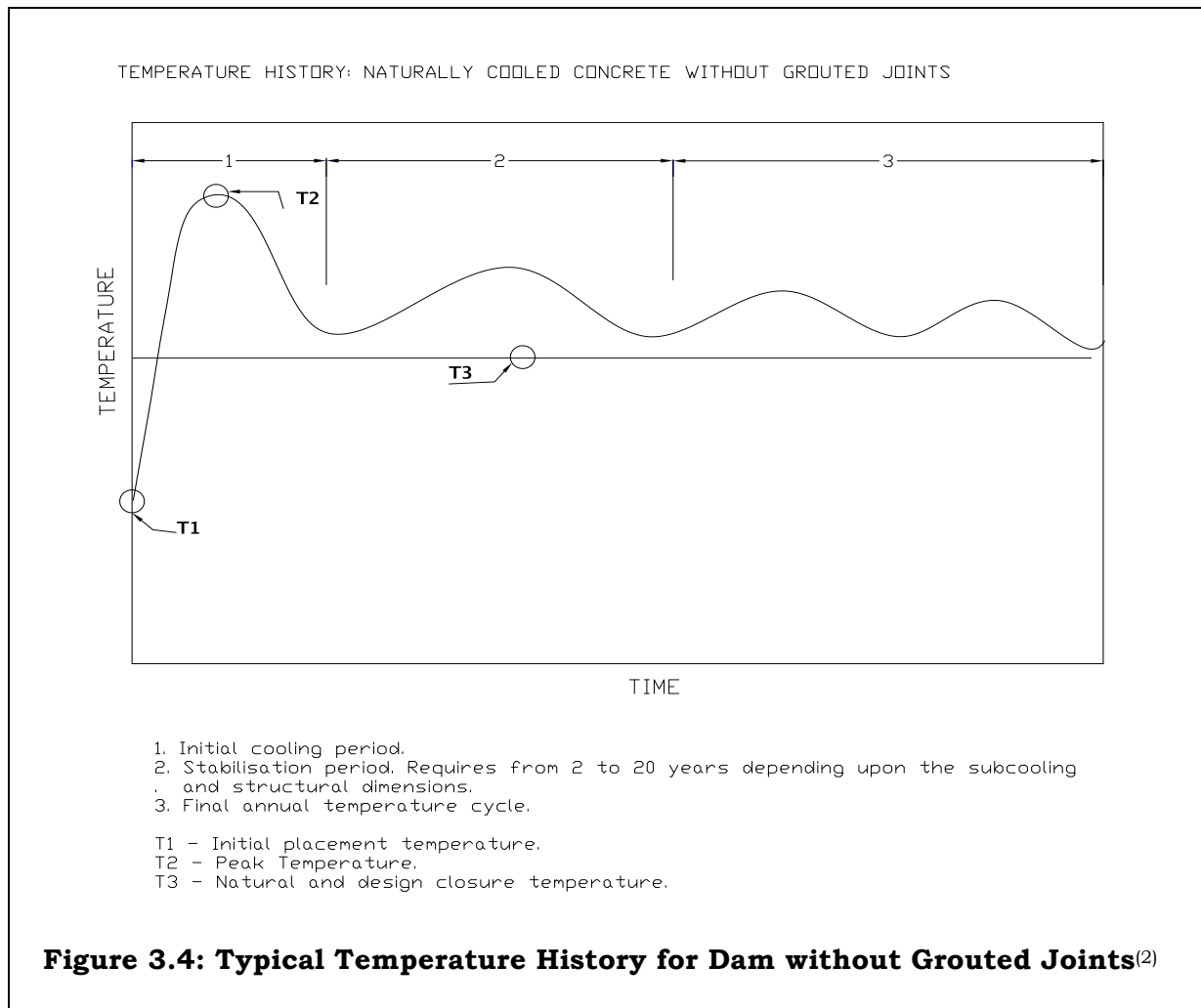
In instances when it is possible to achieve a T3 (natural closure) temperature below the long-term minimum, as illustrated on **Figure 3.4**, no grouting of the contraction joints is necessary and no temperature drop loading will be applicable.

For a conventional mass concrete dam, the long-term structural temperature drop before grouting is accordingly T3 – T4.   If T4 is equivalent to the long-term minimum core concrete temperature experienced, T3 – T4 would also represent the structural temperature drop to be accommodated, should the dam wall not be grouted. With T1, T2 and T4 relatively easily measured, the more difficult issue is to establish T3.

In the case of conventional concrete, it is assumed that most of the compression experienced during hydration heat development is dissipated through creep[4] and, while it is dependent on the placement lift height, the "zero thermal stress temperature", or T3, is taken as 1.5 - 3°C below the maximum temperature experienced during the process of hydration (T2).

The implied design approach accordingly assumes that the long-term thermal cooling that causes shrinkage is incurred by a temperature drop from either the maximum temperature experienced during hydration, or a temperature only slightly lower, down to the lowest core temperature experienced during a particularly cold winter, at some future date[1, 2, 4, 5 & 6]. For a conventional mass concrete, with a total hydration heat temperature rise of perhaps 20°C, this temperature drop (T3 – T4) can accordingly easily exceed 30°C.

TEMPERATURE HISTORY: NATURALLY COOLED CONCRETE WITHOUT GROUTED JOINTS

1. Initial cooling period.
2. Stabilisation period. Requires from 2 to 20 years depending upon the subcooling
   . and structural dimensions.
3. Final annual temperature cycle.

T1 – Initial placement temperature.
T2 – Peak Temperature.
T3 – Natural and design closure temperature.

Figure 3.4: Typical Temperature History for Dam without Grouted Joints[2]

The same principles as applied for the "temperature drop" design in the USACE Engineering Manual on *Arch Dam Design*. 1994[4] are repeated in the USBR's *Design of Arch Dams*. 1977[6]. The latter publication indicates that experience has demonstrated that an effective volume reduction of between 125 and 200 microstrain typically occurs for CVC in mass dam pours for arch dams when post-cooling is applied to reduce the maximum hydration temperature by between 5 and 15°C.

3.6.   EXAMPLES OF CVC DESIGN MODEL APPLIED FOR RCC

3.6.1.   LITERATURE

To confirm the generally accepted application of the above CVC dam design approach to RCC dams, the following examples from referenced literature are provided.

The USACE publication on *Thermal Studies of Mass Concrete Structures* (ETL 1110-2-542). 1997[1] assumes a value for T3 equal to that of T2 in the example thermal analysis presented for the RCC gravity Cache Creek Detention Basin Weir. For the example analysis of a 146 m high RCC gravity dam, T1 is assumed as the temperature in the RCC at the age of 1 day, while T3 is again equated to T2.

In their 2003 paper on thermal stresses in RCC dams, Noorzaei et al[7] stated that the "reference temperature" (T3) is generally established at concrete ages of 0.25, 0.5 or 21 day. However, they considered that the temperature at an age of 30 days, in fact, to be more representative. In the case of mass RCC in a large dam, this temperature would essentially be the maximum experienced during hydration (T2), again suggesting that all of the expansion compression stress is lost to creep.

Zhu[8] describes the thermal issues addressed in the design of a number of RCC arch dams in China, confirming again that conventional CVC behaviour through the hydration cycle is assumed for RCC. While post-cooling has successfully been used prior to the grouting of the induced joints on a number of Chinese dams, the maximum hydration temperature is assumed as the "zero stress" temperature. Unfortunately, no correlation has apparently yet been made in China between the assumed early RCC behaviour and that measured on prototype dam structures.

In their analyses of early RCC stress development during the hydration cycle, Kaitao X & Yun[9] applied creep models developed for conventional concrete, while Carvera et al[10 & 11] used an aging model for a variety of RCC properties and a "solidification theory" creep model, also developed for conventional concrete.

Chen et al [12] varied elastic modulus with time and temperature, whilst applying a CVC model for creep effects, to estimate the structural consequences of hydration heat development and dissipation within a large RCC dam structure. Lackner & Mang[13] proposed a chemoplastic materials behaviour model for RCC to simulate cracking under early thermal effects. While this model was developed for CVC, no comparisons with measured RCC behaviour were included as part of this study.

It is of particular significance to observe that all of the above studies that address the early behaviour of RCC in dams and the consequences thereof failed to compare the predicted behaviour with that actually realised on the prototype structure. Often, it is simply assumed that RCC behaves in the same manner as CVC under the early hydration temperature rise and subsequent dissipation and various models developed for CVC are applied for RCC without any form of verification. No

literature reference seems to exist that evaluates the validity of an assumed CVC behaviour model through comparative measurement on a prototype RCC structure.

PART II: INVESTIGATIONS INTO THE SHRINKAGE & CREEP BEHAVIOUR OF RCC

3.7.   INVESTIGATING SHRINKAGE & CREEP BEHAVIOUR OF RCC

3.7.1.   LITERATURE

3.7.1.1. Creep

When it comes to establishing the applicable levels of creep in young RCC, conflicting opinions, conflicting approaches and conflicting test data are found in literature. The following references provide evidence to support the contention that RCC will often indicate creep equivalent to, or exceeding that of CVC.

Andriolo[14] states that creep in young concrete is mainly affected by the aggregate modulus of elasticity and the filler material in the mix. Due to the fact that the mortar content of an RCC mix will almost always be higher than an equivalent CVC mix, RCC will indicate a higher level of creep than CVC comprising the same aggregates. Generally, aggregates with a low modulus of elasticity will produce concrete with high creep.

In laboratory testing for their thermal and stress analysis of the Cana Brava Dam in Brazil, Calmon et al[15] found values of creep that were typically 20% higher for a low strength RCC (9 MPa at 90 days) than for a slightly higher strength CVC (12 MPa at 90 days).

In their thermal analysis for Mujib Dam in Jordan, Husein Malkawi et al[16] used age-dependent elasticity moduli curves to evaluate stress levels during the early hydration heat development cycle, concluding that these gave rise to a more realistic estimation of stress within the dam structure. Creep was not addressed beyond acknowledging that non-linear behaviour occurs in RCC during early hydration heat-related expansion and that consequently the "zero stress" temperature will be increased above the placement temperature.

To determine creep values for the thermal analysis of Dahuashui RCC arch dam, Penghui et al[17] applied time and stress dependent coefficients, in a multi-term expression, whereby certain constants were apparently derived through testing to an accuracy of 6 decimal places. Unfortunately, no consequential values for creep, or the consequential impact thereof are presented.

Investigations published by Conrad et al[18] discussed the installation and monitoring of modified stress measurement gauges in the CVC facing and RCC close to the upstream face at the Mujib Dam in Jordan. These gauges require RCC with the same characteristics and age as that simultaneously placed on the dam to be compacted within a 400 mm long x 56 mm diameter steel pipe. From the results of these gauges, the study concluded that the zero stress (T3) temperature for the CVC was only marginally beneath the peak temperature experienced during hydration, while the zero stress temperature for the RCC was approximately 3.5°C below the hydration peak. In the case of the CVC, the data suggested that at least 18°C of the effective hydration temperature rise had been lost to shrinkage and creep. In the case of the RCC, the interpretation of the results suggested that approximately 2/3 (or 7°C) of the hydration temperature rise was lost to shrinkage and creep.

While the Stress/Time graph presented for the surface CVC already indicated tension approximately 1 day after placement and the formation of a crack once a tension of 2.1 MPa was reached, the same graph for the RCC indicated very minor levels of tension developing after approximately 4 months and contradictory levels of stress during the subsequent two summer seasons. With a temperature of 37.1°C corresponding to the first incidence of zero stress on the gauge, Conrad interpreted this to be the zero stress temperature for the RCC. Despite never subsequently experiencing a temperature above 37°C, however, compressions of up to 1.1 MPa and maximum tensions of just 0.2 MPa are paradoxically subsequently experienced over the following two years. Observed seasonal temperature variations over this period from approximately 24°C to 37°C correspond with stress variations between 0 and 1 MPa compression. This data would suggest an apparent zero stress temperature of approximately 25°C (rather than 37.1°C), which is below the placement temperature of 30°C. While it may be that the relief of tensile stresses elsewhere through cracking changed the stress state at the gauge in question, there is no direct evidence of such an occurrence and at least the indicated pattern is considered to compromise the certainty with which the zero stress value at the gauge can be defined as 37.1°C. The increasing compression indicated on the surface gauge in question is actually considered to be a reflection of the ongoing shrinkage (thermal and possibly creep) of the internal core RCC.

3.7.1.2. Thermal Modeling

A number of studies have been published that compare the predicted temperatures in RCC dams with measurements on the applicable prototypes[19, 20, 21, 22 & 23] and the technology of temperature prediction has been demonstrated through monitoring to be accurate and reliable. Several of these thermal studies have translated temperatures into the prediction of stress states and while Conrad et al[21] and Yi et al[23] used such studies to back-analyse stress states, only Conrad et al[18] actually

attempted to verify predictions through measurement on a prototype structure, as discussed above.

3.7.2. DISCUSSION

When reviewing the results of the Mujib investigations[18] in respect of the RCC behaviour, it is important to consider a variety of influencing factors, as follows:

- The location of the monitoring point relatively close to the surface can significantly influence the findings. For example, while the hydration heat at the gauge may have been dissipated sufficiently quickly to allow the temperature to follow the ambient cycle very quickly, the core temperature will almost certainly have remained elevated for a number of years further, influencing the stress state at the surface.

- Experience has demonstrated that confirmatory data from a number of instruments are realistically necessary before any quantitative evaluations can realistically be made.

- Bearing in mind the problems associated with the manufacture of RCC cubes and cylinders, it would be reasonable to question whether it is possible to create RCC within a 56 mm diameter pipe with the same characteristics as RCC placed in the dam.

- Presumably as a result of the use of pure cement, without pozzolans, the RCC appears to have experienced a peak hydration temperature, and correspondingly expansion, within only a few days of placement while consequently still of very low strength.

The RCC of Mujib Dam, in which the above instrumentation was installed, was a low strength, lean mix material, with a low cementitious materials content (85 kg/m^3) and a high water content (137 l/m^3 & w/c = 1.61). In such a mix, no excess paste would be available and accordingly, lower densities would be anticipated. The high apparent water content would have been designed to allow a reasonable modified Vebe time and consequently, more moisture would have been provided than required for the hydration process, resulting in an increased tendency for drying shrinkage and an increased susceptibility to creep. While it is not considered possible to draw any specific conclusions on the basis of the limited data available, the nature of the RCC of Mujib Dam is such that some autogenous shrinkage and creep would be expected.

Furthermore, it is considered particularly significant to note of the fact that all of the above studies that indicate equivalent, or greater creep and shrinkage compared to CVC refer specifically to lean, or low cementitious materials content RCC.

3.7.3. APPLYING TYPICAL ANTICIPATED RCC BEHAVIOUR

In the core of a large RCC dam with a mix including a large proportion of pozzolan, the hydration heat builds up to a maximum over a period typically of approximately 90 days, with perhaps 85% of the peak temperature achieved within 30 days of placement[6 & 24]. According to the various literature for which creep testing is referenced[25, 26 & 15], RCC that is loaded at an age of say 15 days, and which loading is sustained for 365 days, will creep at a rate of between 50 to 100 x 10^{-6} per MPa stress. For a temperature rise of approximately 15°C, an average (sustained) elastic modulus of say 10 GPa and a thermal expansion coefficient of say 10 x 10^{-6}/°C, a consequential compressive stress of 1.5 MPa would be developed as a result of the hydration temperature rise. Consequently, creep of the order of 75 to 150 x 10^{-6} would be anticipated. Such creep would effectively increase the reference, or zero stress temperature in the RCC by between 7.5 and 15°C. On the basis of this type of calculation, it can clearly be seen why it would be considered appropriately conservative to set the reference temperature equal to the maximum hydration temperature (T2).

Applying Schrader's[27] graphical relationship between strength at the time of initial loading, and creep and assuming an effective initial strength of 5 MPa at loading, would indicate a 365 day creep of approximately 70 microstrain per 1 MPa containing stress. For a sustained temperature rise of 15°C in the centre of a large dam, the containing stress may be approximately 1.5 MPa, for which a total creep of approximately 105 microstrain would accordingly be anticipated. This is of a similar order to other indications.

PART III: EVIDENCE TO SUPPORT REDUCED SHRINKAGE & CREEP IN RCC

3.8. NOTIONAL EVIDENCE OF SHRINKAGE & CREEP BEHAVIOUR OF RCC

3.8.1. LITERATURE

3.8.1.1. Drying Shrinkage

The USACE's Engineering Manual *Roller Compacted Concrete.* 2000[2] states that while drying shrinkage is governed primarily by the water content and the mixture and characteristics of the aggregates, RCC drying shrinkage is similar, but generally lower than CVC, as a consequences of the lower moisture contents. However, the effects of drying shrinkage are usually considered to be negligible and are consequently ignored for mass concrete in dams, as moisture cannot escape from

the interior and only surface zones are accordingly likely to experience any drying shrinkage.

Laboratory investigations by Xia et al[25] and Kaitao[8] suggested that RCC indicates typical drying shrinkage of the order of 50 to 75% of that applicable for the equivalent CVC. Dependent on the aggregates used, a total 90 day drying shrinkage of 100 to 300 microstrain can be anticipated. While drying shrinkage in RCC appears to continue for approximately 5 months after compaction, the majority has occurred within the first 90 days.

In the ICOLD Bulletin 126, *Roller-Compacted Concrete Dams.* 2003[29], it is stated that drying shrinkage is limited to the exposed surfaces of the RCC mass.

3.8.1.2. Autogenous Shrinkage

The USACE's Engineering Manual *Roller Compacted Concrete.* 2000[2] states that autogenous shrinkage can be a significant factor for all mass concrete and is particularly dependent on the proportions of the mix and particularly the content and type of aggregates. Autogenous shrinkage occurs over a significantly longer period than drying shrinkage, but can be negligible, or even take the form of an expansion.

In Chapter 20 of the *Concrete Construction Handbook.* 2008[27], Schrader briefly discusses autogenous volume changes, stating that this cannot be reliably estimated in RCC, or CVC in mass dams. However, in some RCC, early expansion has been followed by later contraction, while the reverse has also been observed.

The ICOLD Bulletin 126, *Roller-Compacted Concrete Dams.* 2003[29] states that autogenous changes in volume are normally inconsequential.

3.8.1.3. Creep

Testing on a number of RCCs and CVCs by Zhu et al[26] indicated a general pattern of substantially lower creep in RCC than CVC. Testing by Xia et al[25] for the Yantan coffer dam suggested very similar levels of creep for RCC and CVC, with fractionally higher creep in RCC loaded at a very early age and significantly higher creep in CVC loaded at an age of 1 year. This work would seem to be confirmed by testing by Conrad et al[18], which indicated a lower early elastic modulus and a higher long-term modulus for low-cementitious RCC, when compared with an equivalent CVC.

In Chapter 20 of the *Concrete Construction Handbook.* 2008[27] Schrader states that a very high creep rate, with dramatic reductions in stress over time, is possible with low-cementitious-content RCC mixtures. This characteristic is seen as beneficial in respect of improving the crack resistance of massive placements subject to thermal stress by reducing the sustained deformation modulus (E value). Schrader[27] goes on to state that assuming creep in tension is equivalent to creep in compression

can be conservative, particularly for mixtures containing a relatively high content of coarse aggregates and that aggregate-to-aggregate contact can decrease creep in compression. Comparing creep measured across a large number of RCC samples, Schrader observed that specific creep does not increase significantly for RCC with a compressive strength greater than 15 MPa at first loading. The same graph (Figure 20.34) suggests that RCC of higher strength tends to indicate lower creep than equivalent strength CVC. For RCC of a lower strength than 5 MPa at first loading, however, creep increases exponentially with reducing strength.

Testing for the Miel Dam in Columbia, López et al[28] demonstrated a very significant decrease in creep with increasing cement content. Loading the specimens at 7, 28 and 90 days, the reduction in creep with increasing cement content was progressively more pronounced the earlier the initial loading.

3.8.1.4. Total Shrinkage

The USACE EM 1110-2-2006 guideline on *Roller Compacted Concrete.* 2000[.(2)] observes that typical maximum joint openings on RCC dams generally vary between 1 and 3 mm, for typical induced joint spacings of between 15 and 40 m. These observations are in stark contrast with the extent of joint openings predicted on the basis of the characteristics apparent through the referenced laboratory testing and analysis. For joint spacings of 15 to 40 m, "accepted theory" would anticipate maximum joint openings of between 5 and 15 mm.

The ICOLD Bulletin 126, *Roller-Compacted Concrete Dams.* 2003[29] states that induced joints are usually spaced at greater distances than typically applied for CVC dams.

The weight of notional evidence of reduced shrinkage in respect of RCC compared to CVC is particularly strong at the De Hoop Dam[30], which is an 85 m high RCC gravity dam currently under construction on the Steelpoort River in Mpumulanga. At De Hoop Dam, cracking has been observed in a number of the CVC concrete pours, including the mass concrete outlet block. The boat slipway, on the other hand, which was cast as part of the final RCC trials, demonstrates an RCC placement of several hundred metres in length, manufactured with the same materials, without a single trace of cracking. While no RCC placement lifts exceeding 2.4 m have yet been achieved, no cracking at all is evident on the various stretches of RCC placed to date on the dam wall.

While the related investigations and the associated Thermal studies are described in more detail in Chapters 4 and 5, important observations of the apparent early behaviour of the RCC can be made at Changuinola 1 Dam. Cracking in the surface of the RCC has been observed on all large blocks left exposed for periods exceeding approximately 3 weeks. Simulation through the Thermal study reveals these cracks to form as a result of excessive temperature gradients and the associated differential expansion of the RCC mass, compared with the surface. Applying a

scenario with no creep to represent the worst-case situation, the development of these cracks was predicted with some accuracy. Applying internal creep (or total shrinkage) of just 25 microstrain in the Thermal analysis was sufficient to substantially reduce the likelihood of these cracks forming during the first three months after placement.

3.8.2.   DISCUSSION

The general literature discussion on the subject suggests that creep in RCC under early thermal load is beneficial in reducing the stresses developed through temperature gradients[2 & 27]. In more extreme climates and in the case of RCC mixes with a relatively high heat of hydration, this is undoubtedly true. However, what might be a beneficial effect in mitigating stresses developed through short-term thermal gradients, is in fact disadvantageous in increasing the effective long-term temperature drop.

To illustrate this point quantitatively, it is considered of value to review the impacts of the autogenous shrinkage and creep typically assumed in accordance with a "Traditional RCC Materials Model", which might assume a "typical" total volume reduction of 150 microstrain to account for the combined impacts of autogenous shrinkage and stress relaxation creep during thermal expansion. For a further temperature drop of the order of 8°C to the long-term average core body temperature and a coefficient of thermal expansion of $10 \times 10^{-6}/°C$, total shrinkage of the order of 230 microstrain might be anticipated for RCC in the core of a large dam. Assuming RCC with a sustained elastic modulus of 15 GPa, total strain of this order would develop tensions of 3.45 MPa, well in excess of the tensile strength capacity of any RCC.

For transverse joints spaced at say 20 m centres, such shrinkage would suggest joint openings of 4.6 mm. Over a dam wall length of 270 m, as is the case for Wolwedans Dam, total concrete "shrinkage" would equate to approximately 62 mm.

In the cases of all of the dams for which the author of this work has data, no evidence is available to suggest a shrinkage, or net volume reduction, approaching the levels predicted by the traditional theory. In fact, quite the opposite and the data to be presented as part of this thesis firmly contradict the theoretical behaviour of RCC, suggesting substantially lower levels of autogenous shrinkage and creep under early thermal loading.

PART IV: A COMPARISON OF THE MATERIALS CHARACTERISTICS OF HIGH-PASTE RCC COMPARED TO CVC IN DAMS

3.9. A LITERATURE REVIEW OF SHRINKAGE & CREEP IN CONCRETE

3.9.1. GENERAL

Before going on to review RCC in dams against those characteristics that make a concrete more, or less susceptible to shrinkage and creep, it is first worth briefly reviewing and discussing the phenomena of shrinkage and creep in concrete. In the process of a literature review, it is possible to develop a greater understanding of the associated differences in behaviour between RCC and CVC. Consequently, it is also possible to isolate those characteristics of an RCC mix that should be given specific attention in design when it is important to minimise shrinkage and creep.

Shrinkage and creep in concrete are very similar[31], inter-related effects and the susceptibility of concrete to both of these phenomena relates to the nature of its composition and the manner in which it is formed and develops strength. As the cementitious materials in concrete hydrate, they form a gel, which has a smaller volume than its constituents. As the cement paste shrinks in this process, the bond between the paste and the aggregates and the structure between the different sized and shaped aggregate particles serve to resist a general shrinkage of the concrete. The net result is a structure with internal residual shrinkage stresses and micro-cracks.

To complicate this situation further, the matrix experiences expansion stresses as a consequence of the heat evolved during the exothermic reaction of hydration. As a result, hardened concrete is actually a complex network of micro-structures, internal stresses and micro-cracking, whose consequential susceptibility to creep under load is obvious.

The extents of early autogenous/drying shrinkage and creep in concrete are dependent on a number of factors, primarily related to the paste content and the characteristics of the mortar sand[31 & 38].

In the following sections, shrinkage, creep and the typical early behaviour of concrete are discussed.

3.9.2. SHRINKAGE

Shrinkage in concrete comprises two components; autogenous shrinkage, which develops immediately after setting, and drying shrinkage, which is a consequence of the long-term loss of moisture. Autogenous shrinkage is caused by the consumption of water in the hydration process, or could be perceived as a consequence of the gel formed through hydration being of a reduced volume than its constituent components, of cementitious materials and water.

Conventional concrete will usually contain more water than can chemically be combined with the cement, with the consequence that, in a normal environment, water will eventually be lost from the concrete, resulting in drying shrinkage. Autogenous shrinkage experienced and measured in concrete is a small fraction of that which occurs in the cement itself[33]. The aggregate particles in concrete dilute the effect of the cement shrinkage and the bond between the aggregates and the cement paste causes a restraining effect on the overall shrinkage.

The lower the w/c ratio in concrete and the greater the degree of hydration, the greater the volume of the hydration product (gel) and the greater the ratio of gel pore to capillary pore volume. As the paste dries, it loses capillary water first, then absorbed water and then gel-pore water. As a consequence, low cementitious materials content concretes demonstrate a greater tendency for both autogenous and drying shrinkage.

The chemical composition of cements used in concrete influences the extent of shrinkage that can be expected, with the tri-calcium aluminate phase and the gypsum content being of specific importance[33]. An optimum sulphate content appears to exist for minimum shrinkage, while higher alkali cements indicate higher shrinkages.

Investigations by the National Building Research Institute (NBRI)[33] demonstrated that a relatively good correlation exists between the shrinkage of mortar and the specific surface of the mortar and its constituent aggregates. Furthermore, aggregate properties such as size and grading affect shrinkage of concrete indirectly as a consequence of their influence on the mix water requirements[32].

The use of aggregates that themselves demonstrate drying shrinkage can increase concrete shrinkage very substantially.

3.9.3.   CREEP

Creep in concrete is associated with the presence of mobile water in the paste and accordingly, the greater the moisture content, the greater the creep[31] and the greater the component of the moisture that is not consumed in the hydration process, the greater the susceptibility to creep.

Normal density aggregates of hard gravel or crushed rock do not usually exhibit creep at the stress levels typical of normal concrete and particularly mass concrete. On the other hand, aggregate grading and volume concentration have a significant, if indirect, influence on concrete creep, with a higher aggregate content resulting in less creep. This is unsurprising, as the higher the concentration and elastic modulus of the aggregate, the higher the restraint against creep exerted on the paste.

The impact of admixtures on concrete creep has demonstrated some significant variability, with the effects apparently varying dependent on the specific conditions and the specific methods of testing. Various testing work in South Africa has

demonstrated a substantial influence of aggregate type on creep[32]. While this work also took into account the water demand of the aggregates, creep was found to be a variable phenomenon that necessitated specific laboratory testing in critical cases.

The intensity and rate of drying of concrete have been found to be of specific influence on the extent of creep subsequently observed[34]. Work by Grieve[35] found that fly ash has a benefit in reducing creep in concrete, while Ground Granulated Blastfurnace Slag (GGBS), on the other hand, can sometimes result in increased creep[33].

A significant amount of experimental work has been undertaken on the creep behaviour of conventional concrete and a number of algorithms have been developed to predict creep at various ages[31 & 33]. In view of the fact that all such work is based on empirical observation, the documented observed differences in the early behaviour of RCC compared to CVC must compromise the value of any of these approaches in respect of RCC.

3.9.4.   PROPERTIES OF CONCRETE WITH PARTICULAR INFLUENCE ON SHRINKAGE & CREEP

In summary of the above, factors that have been demonstrated to impact shrinkage and creep in concrete include the following:

- A high w/c ratio, as this tends to imply that more moisture is present than required for hydration and this will eventually be lost with consequential drying shrinkage,

- Excess water not consumed in the hydration process increases the susceptibility of concrete to creep,

- A dry environment and direct exposure to the atmosphere increase drying shrinkage,

- The rate of drying of concrete increases creep,

- A high aggregate content reduces shrinkage and creep,

- A smooth aggregate surface (rounded gravels) reduces the aggregate/paste bond and accordingly gives rise to increased shrinkage and creep,

- A high proportion of fine aggregates and particularly non-cementitious fines increases shrinkage, and

- The use of fly ash in concrete decreases shrinkage and creep.

3.9.5.   OTHER IMPORTANT INFLUENCES

Techniques for the manufacture of mortar and conventional concrete test samples relatively accurately replicate the process applied in full-scale construction. The methods used for the manufacture of RCC cubes and cylinders, on the other hand do not particularly accurately replicate the effect of roller compaction applied on full-scale construction. Furthermore, the difficulties inherent to the manufacture of RCC samples on a laboratory scale give rise to a comparatively broad spread of test results. In comparison to CVC, for which many more years of technological development and a significantly broader range of utilisation exist, these problems, limited experience in a developing technology and a use generally limited to dam construction can be seen to have compromised the level of understanding of the early shrinkage and creep behaviour of RCC developed to date.

Drying shrinkage is measured in the laboratory in a mortar form, while creep is measured on concrete moulded in cylinders with the > 50 mm aggregate removed. Creep is typically tested at loads up to 40% of the compressive strength of the sample at the start of testing[37]. Neither of these testing conditions replicate the insulated, contained and relatively low stress environment typical of the core of a dam.

Conrad et al[38] investigated the stress-strain behaviour of low strength RCC of between 6 hours and 365 days age. While the RCC mix used for this research was of a low cementitious materials content (85 kg/m³) and a very high w/c ratio (1.61), the complexity of the RCC moulding process was also recognised as a factor that gave rise to a more pronounced variability in the results recorded across a number of samples of the same material. The investigations found that the development of the deformation modulus in RCC was quite different to that of CVC and concluded that common approaches for the temporal evolution of the modulus of deformation of concrete in compression are not applicable for low-cementitious RCC. This testing, however, suggested that the deformation modulus for a low-cementitious materials content RCC would be lower than that of an equivalent CVC at early ages, but higher at later ages.

3.10.   HIGH-PASTE RCC IN LARGE DAMS

In respect of a high-paste RCC within a large dam body, the conditions are perhaps ideal, as the factors that tend to increase the tendency of concrete to shrink and creep are not generally evident. The following factors are important:

- In a high-paste RCC, the w/c ratio will be low (0.5 to 0.65) and all available moisture will be consumed in the hydration process,

- In a large dam body, the RCC is well protected against rapid and surface drying and any form of drying shrinkage is unlikely to be a factor at the core of a dam,

- Even high paste RCC mixes contain a high aggregate content compared to a high strength structural concrete, and

- Fly ash, or an active pozzolan, is often used in high paste RCC.

Sembenelli & Shengpei[39] also considered that the slower rate of hydration heat evolution of RCC compared to CVC would imply a comparatively higher modulus in the case of RCC at the time of maximum temperature-induced compressive stress. Suggesting that the peak hydration temperature in mass CVC is usually reached within 3 to 7 days of placement, compared to 28 days or more in the case of RCC containing a high percentage of pozzolanic materials, it was considered that the modulus of elasticity in the case of RCC would be higher by the time the peak hydration temperature was reached. As a result, RCC should be less susceptible to creep under the associated contained expansion (compressive) stress. Putting this supposition into the context of the findings of the investigations addressed in this study, the records for the dams studied suggest that approximately 70% of the hydration temperature rise in RCC is typically evident within 3 to 5 days of placement. Consequently, it can be stated that while RCC may gain some benefit due to a slower and lower hydration heat development, that benefit is not likely to be particularly significant in respect of reducing its susceptibility to creep under contained expansion stresses.

It is considered likely that fly ash in an RCC mix adds significant benefits, through increasing the mobility of the paste and slowing the rate of moisture loss by reducing permeability. In view of the fact that fly ash has been demonstrated to reduce creep in concrete[35], it is considered likely that the autogenous shrinkage of cementitious paste is reduced when fly ash is used in relatively large proportions.

As a result of the various factors listed, however, it is considered un-surprising that shrinkage and creep effects in high-paste RCC are in fact not as prevalent as is the case in an equivalent CVC.

It is also considered that the method of compaction is likely to decrease the susceptibility of RCC to shrinkage and creep. If it can be stated that the skeletal structure formed by the aggregates in concrete acts to restrain the shrinkage of the paste during hydration, the compaction energy exerted on RCC undoubtedly ensures that

Plate 3.2: A Modern RCC at De Hoop Dam

this skeletal structure is better developed, with inter-aggregate particle contact, and stronger than will be the case for immersion vibrated compaction.

3.11. CONCLUSIONS

3.11.1. SUMMARY

On the basis of the foregoing literature study, the following indications in respect of the early shrinkage and creep behaviour of RCC can be deduced:

- In terms of dam design, RCC is often assumed to behave in the same manner as CVC, in terms of shrinkage and creep performance.

- Dam design approaches generally simplify creep and shrinkage behaviour into an assumed thermal contraction.

- The autogenous shrinkage and creep characteristics of RCC can be highly variable.

- Drying shrinkage effects are negligible within the core of a large dam structure and can be ignored for the purpose of the investigations addressed into the early behaviour of RCC in large dams.

- Creep can be expected to be very high in low strength, low cementitious materials content RCC mixes.

- Creep and autogenous shrinkage will be reduced in concretes with low water contents, high aggregate contents and effective particle-to-particle contact within the aggregate skeletal structure.

- The use of fly ash in RCC is beneficial in respect of reduced shrinkage and creep.

- Whereas a high paste content in CVC usually implies high autogenous shrinkage and creep, "High-paste RCC" would be considered to indicate a relatively low-paste content, and actually indicates a relatively large aggregate content and a low water content, compared to CVC.

On the basis of the preceding review, it is quite clear that the best performance from RCC, in respect of least shrinkage and creep during the hydration cycle, can be anticipated in a high-paste, low water content mix, with well-graded, high quality aggregates and particularly sand with a relatively low compacted void ratio.

With its high aggregate content, low water content, relatively high strength and effective particle-to-particle aggregate skeletal structure, as a concrete, the characteristics of a "high-paste" RCC are probably as ideal as possible for the reduction of autogenous shrinkage and creep.

Evaluating the RCC of the dams investigated as part of this study against these requirements, they would rank as Wolwedans, Knellpoort, Changuinola 1, Çine and Wadi Dayqah; realistically in line with expectations as to apparent level of shrinkage and/or creep.

Early shrinkage and creep in concrete are interdependent effects that occur simultaneously during the process of maturation. The early development of internal shrinkage creates a susceptibility to creep under load. With negligible drying shrinkage in the core of a mass concrete block, the important shrinkage is autogenous shrinkage. While shrinkage and creep are used together in this Thesis, the dominant effect is undoubtedly manifested as creep; a stress relaxation that occurs when the temperature rise associated with the hydration process attempts to cause thermal expansion in immature concrete.

3.11.2. THE WAY FORWARD

On a qualitative basis, the above review has allowed the characteristics of "high-paste" RCC to be demonstrated to be as ideal as possible for a concrete in respect of the reduction of creep and shrinkage. The various information and references quoted, however, confirm that no quantitative analyses have yet been made on a large-scale of the creep and autogenous shrinkage behaviour typical of high-paste RCC in a dam.

The discussions confirm the general problem of sample manufacture and the fact that it is not realistically possible to recreate the full-scale compaction conditions and effect inherent to RCC construction on a laboratory scale.

Having introduced the dams instrumented and discussed the major issues in respect of design and the early behaviour of RCC in dams in this Chapter, the instrumentation data from the dams addressed will be presented in Chapter 4.

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