# CHAPTER 8

# 8. STUDY CONCLUSIONS

## 8.1. INTRODUCTION

In this Chapter, the author summarises the investigations and studies undertaken, presents the conclusions that can be drawn and discusses the important implications and applications of his research in respect of the future design of large RCC dams.

## 8.2. BACKGROUND

### 8.2.1. RCC DAMS: OBSERVATION & DESIGN

The author of this work has over 25 years experience in the design and construction of major RCC dams and over this period, his observations have repeatedly suggested a quite different behaviour and performance for high-paste RCC in dams compared to that universally assumed and applied in design. The behaviour of concrete during the exothermic process of hydration and the subsequent heat dissipation has always required careful management in the construction of large dams. With a continuous, horizontal construction and an approach of inducing, rather than forming, transverse joints, these issues are of equal if not greater concern in the case of RCC.

Yet, designers and design literature still fail to take cogniscance of the differences between CVC and RCC. There are undoubtedly a number of reasons for this fact; the difficulties associated with testing the early properties of RCC, the variability of RCC types and approaches applied to date and most importantly, the fact that assuming early CVC behaviour properties for RCC is generally conservative, at least in the case of gravity dams. However, as RCC arches and arch/gravity dams gain increasing acceptance, the unqualified application of CVC models, or models that incorrectly predict the behaviour of RCC, carries a certain number of risks.

Structurally, RCC is substantially more susceptible to shrinkage and creep in an arch dam than is CVC, due to the fact that an RCC dam is not constructed in vertical monoliths, with groutable joints in between, and as a result of the fact that cooling pipe loops cannot be as easily installed. It is consequently imperative to be able to quantify the respective impacts of temperature drop loads on RCC in arch dams and accordingly to understand when and by how much induced joints are likely to open.

### 8.2.2. LITERATURE & REFERENCES

Much has been published over the years on the design and construction of RCC dams. Amongst this work, a constant thread can be observed in the fact that whenever the early thermal behaviour of RCC is analysed, the shrinkage and creep behaviour characteristics of CVC are applied. While the author would have seen significant advantage in being able to reference similar and related work on RCC, a large part of the motivation for the investigations undertaken was the apparent absence of earlier studies that have investigated the differences between early CVC and particularly high-paste RCC behaviour on prototype structures.

It is considered extremely pertinent to note that the literature searches undertaken during the course of the studies addressed herein repeatedly encountered cases that simply assumed and applied CVC materials models for RCC.

Certainly, some work has been undertaken to investigate the early drying shrinkage and creep behaviour of RCC, but this has been laboratory-based and most specifically related to lean mix (low strength) RCC. Consequently, very little of the published literature and investigation findings has much relevance to high-paste RCC.

While many thermal and structural analyses of RCC dams have been presented in technical literature, not a single one has been encountered that compares the actual behaviour of RCC on a prototype dam structure with that predicted through analysis.

### 8.2.3. RCC MATERIALS TESTING

One of the most significant reasons that RCC materials models have to date not realistically represented RCC behaviour in application is considered to be the methods applied for laboratory testing.

When the behaviour of high-paste RCC in a dam structure is so dependent on the aggregate skeletal structure developed through the method of construction, it is essential that this same structure be recreated in samples tested. Realistically, this cannot be achieved in a laboratory. The process of kneading and orientating the aggregate structure that happens on a large scale beneath a vibratory roller simply cannot be recreated with the tools available on a laboratory scale, or within the context of a 150 mm mould, or cylinder. Drilled cores will better reflect reality. However, even the scale of a 150 mm diameter core is probably too small. Furthermore, it is notoriously difficult to extract a core from immature RCC, implying that the current methods available for early creep and shrinkage testing of RCC simply cannot produce results with adequate levels of confidence. Testing RCC mortar, or samples compacted with the coarse aggregates screened off, in a small cube, or cylinder can never realistically be expected to reflect the properties of the in situ material.

Due to the compaction method applied, it is also more than likely that the aggregate skeletal structure would indicate greater strength in RCC in a horizontal, rather than a vertical direction. In view of the fact that the majority of strength and elasticity testing on RCC samples is likely to be orientated in a vertical direction, the validity of the results is compromised in respect of the critical horizontal behaviour characteristics that are of most relevance to temperature effects in arch dams.

### 8.2.4. FOCUS OF WORK ADDRESSED IN THIS STUDY & RESEARCH OBJECTIVES

The primary focus of the work addressed in this study was to demonstrate that high-paste RCC in large dams does not necessarily behave in the same manner as CVC under the early hydration heating and cooling cycle. On the basis of observation and instrumentation data records at five prototype RCC dams, as presented in Chapter 2, indications of RCC behaviour are derived. For the first time in the development of the technology, this study subsequently develops a new understanding of the behaviour of high-paste RCC in a large dam through a comparison of the three-dimensional structural behaviour of a prototype structure with that predicted using a comprehensive Finite Element model.

Through the research and investigations completed, the key research question is answered and it is consequently demonstrated that the traditional approach to dam design for shrinkage and creep during the hydration cycle is not applicable in the case of high-paste RCC dams.

## 8.3. THE EVIDENCE OF RCC MATERIALS BEHAVIOUR IN LARGE DAMS

### 8.3.1. GENERAL

The first stage of investigation of the apparent early behaviour of RCC involved a direct interpretation, as far as this was possible, of measurements recorded through the instrumentation installed at Wolwedans and Knellpoort Dams in South Africa, Çine Dam in Turkey, Wadi Dayqah Dam in Oman and Changuinola 1 Dam in Panama, as presented in Chapter 4.

### 8.3.2. WOLWEDANS & KNELLPOORT DAMS

The instrumentation data recorded at both the Wolwedans and Knellpoort dams suggests a relatively linear relationship between temperature and strain across the induced joints (see **Figures 8.1** and **8.2**).

Making a general interpretation of the measurements made, it is apparent that the core RCC experiences compression at temperatures above placement and tension at temperatures below that at placement.

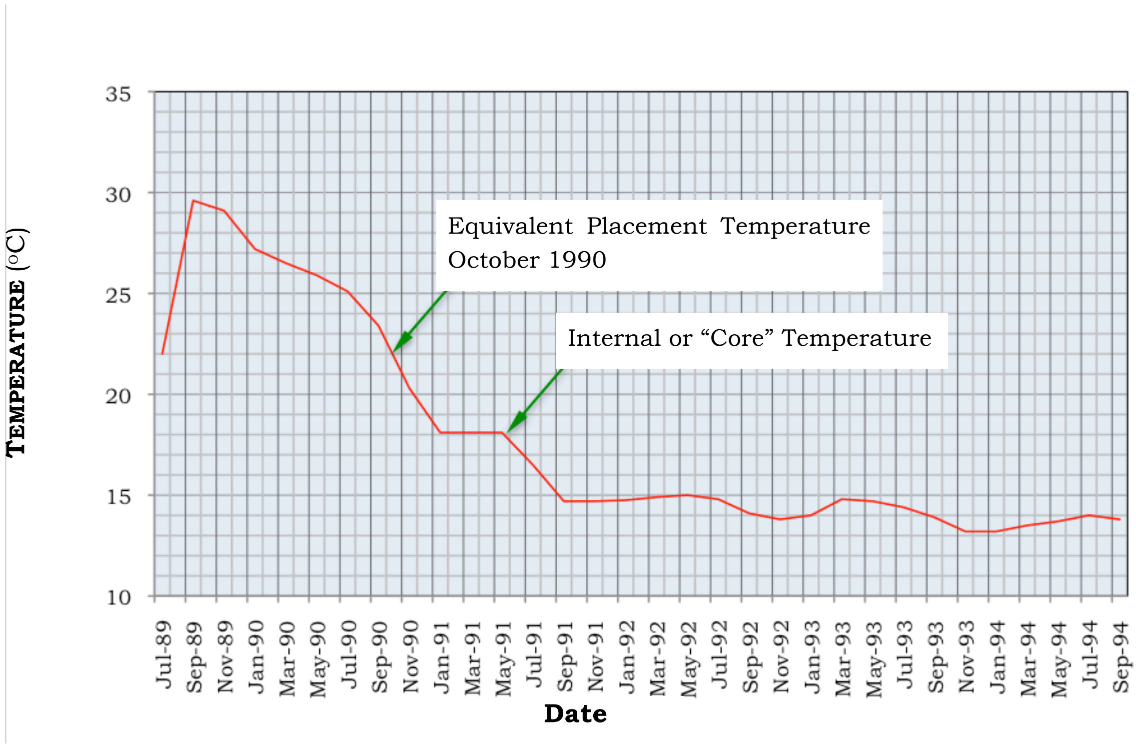

**Figure 8.1: Typical "Core" Temperature – Time Curve for Wolwedans**

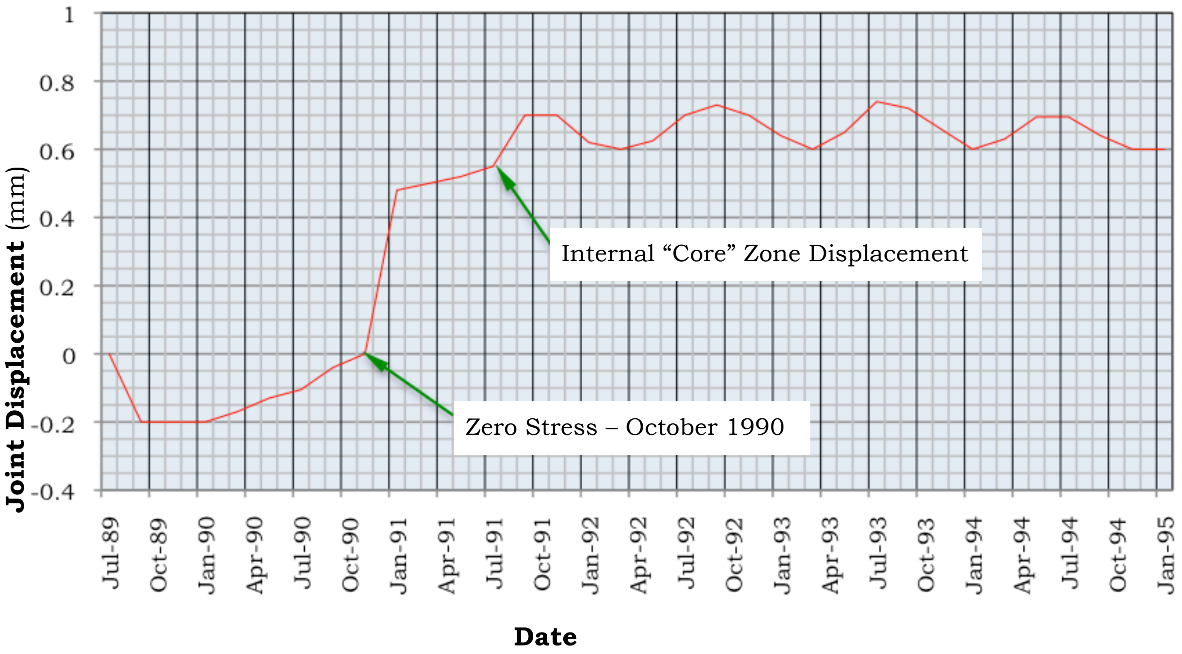

**Figure 8.2: Typical "Core" Joint Opening – Time Curve for Wolwedans**

In the case of Wolwedans Dam, only five of the 27 induced joints opened and of these, only three central joints were of significance, with the outer two realistically beyond the extent of the arch action. At the three open joints, the measured openings were substantially less than a linear application of the apparent temperature drop from placement would suggest.

By the time that the hydration heat had effectively been dissipated from the dam structure at Wolwedans, the reservoir had essentially filled and accordingly, a certain amount of structural displacement had occurred. Consequently, the reason for the induced joint openings being less than anticipated could not be determined, whether it was the result of residual tensions between the induced joints, or structural deflection, or some other reason.

### 8.3.3. ÇINE DAM

The instrumentation data for Çine Dam illustrates a clear pattern. While the temperature within the core of the dam has remained elevated, with no significant dissipation yet evident, the Long-Base-Strain-Gauge-Temperature-Meters (LBSGTMs – also termed SGT gauges) have indicated no strain relaxation. The fact that a linear increase in closure strain was demonstrated on the induced joints when an increase in temperature was caused, between 1 and 2 years after placement, by the downward flow of heat within the structure, however, further provides strong evidence that no significant creep, or shrinkage in the RCC could have occurred, as illustrated in **Figures 8.3** and **8.4**.

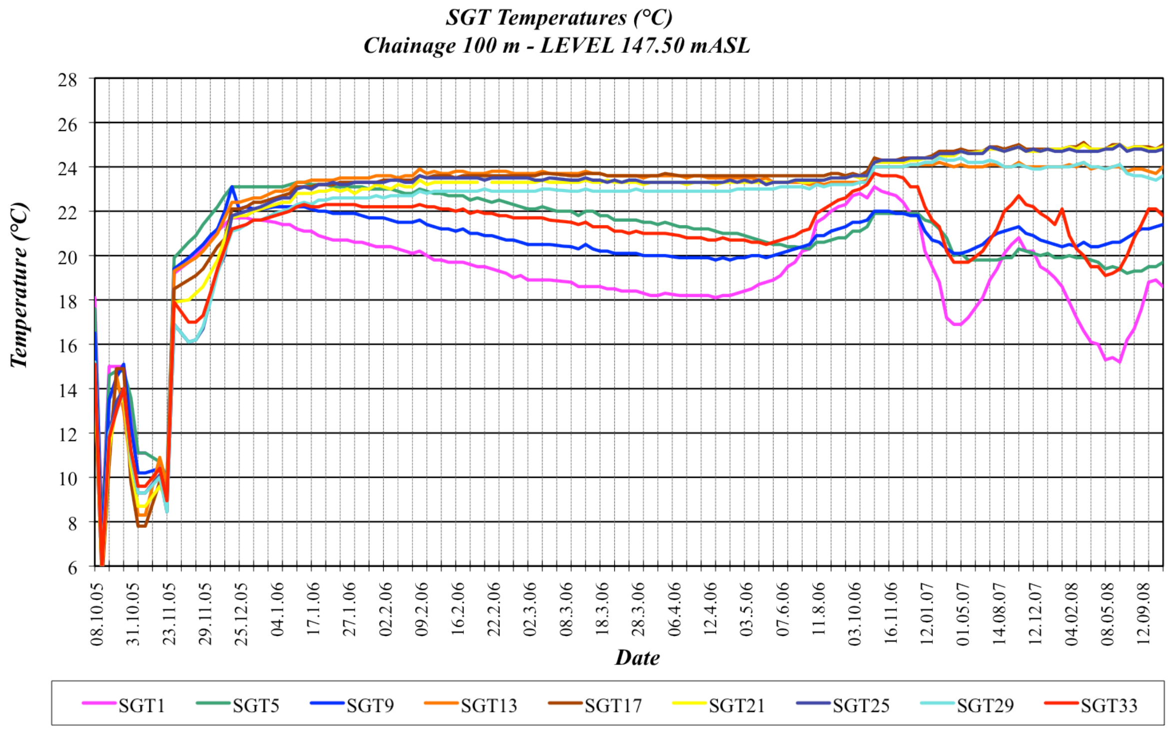

**Figure 8.3: Typical "Core" & Surface Temperatures for Çine Dam**

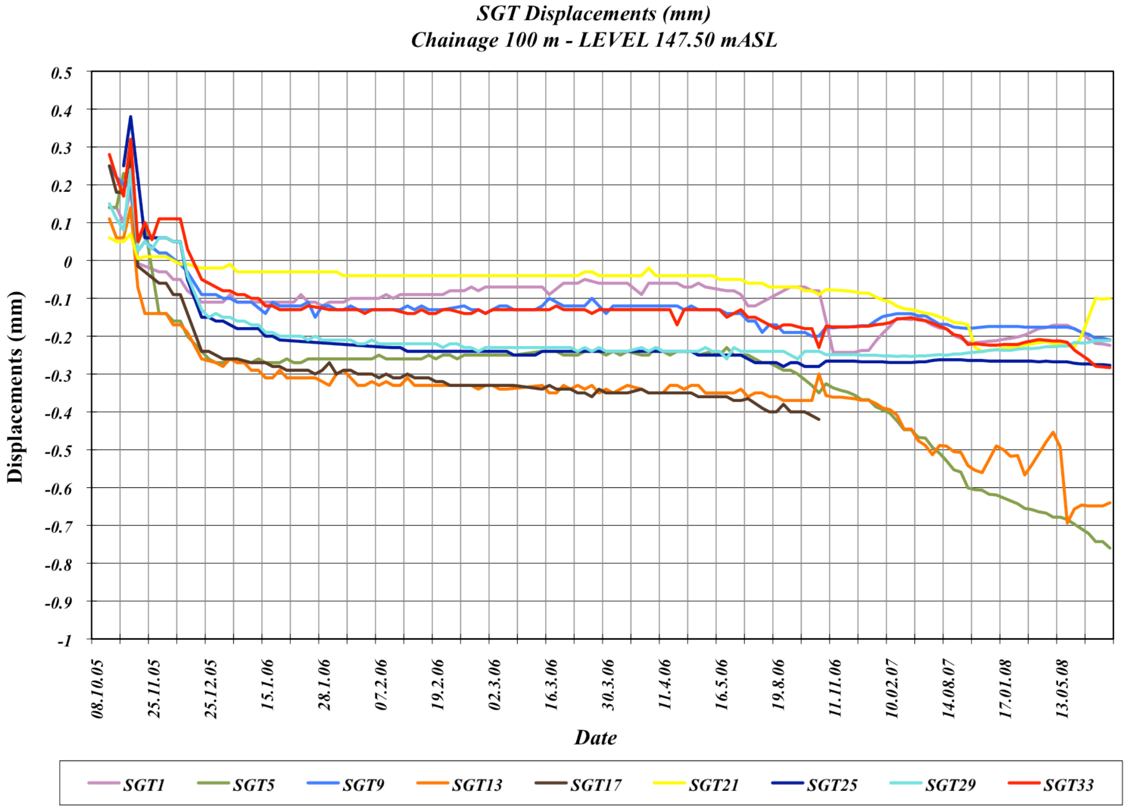

**Figure 8.4: Typical "Core" Joint Displacements for Çine Dam**

Measuring temperature and strain in the RCC at Çine Dam in an upstream-downstream direction (SGA gauges), in which the RCC is subject to less restraint, a total maximum thermal expansion strain of the order of 120 microstrain was recorded, as illustrated in **Figure 8.5**. For a hydration temperature rise of approximately 14°C, this strain translates into an equivalent RCC thermal expansivity of 8.4 x $10^{-6}$/°C.

Over the period between 3 and 7 months after RCC placement, a strain relaxation of approximately 12.5% was measured, as illustrated in **Figure 8.6**, despite the fact that the temperature remained essentially constant.

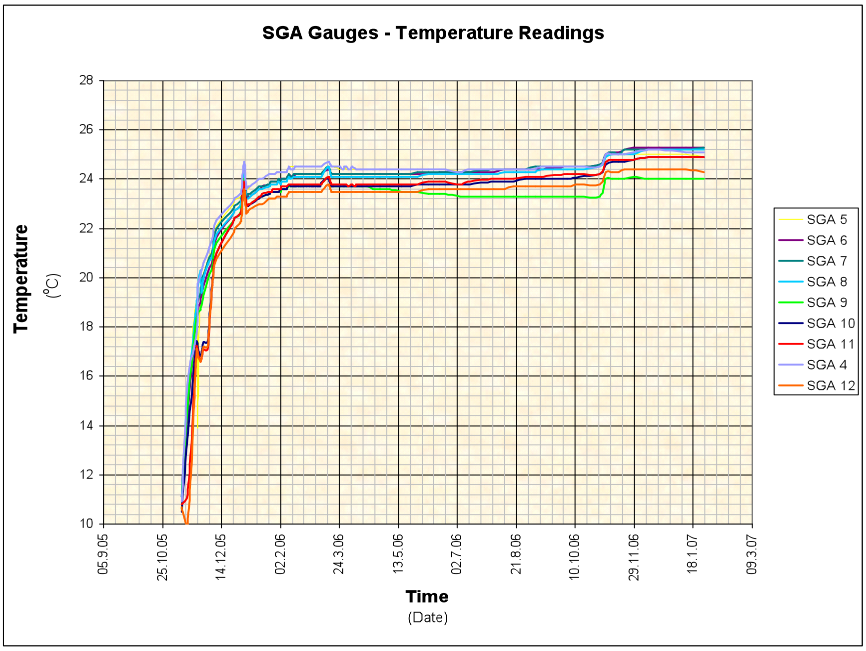

**Figure 8.5: Temperature on U/S – D/S Strain Gauges**

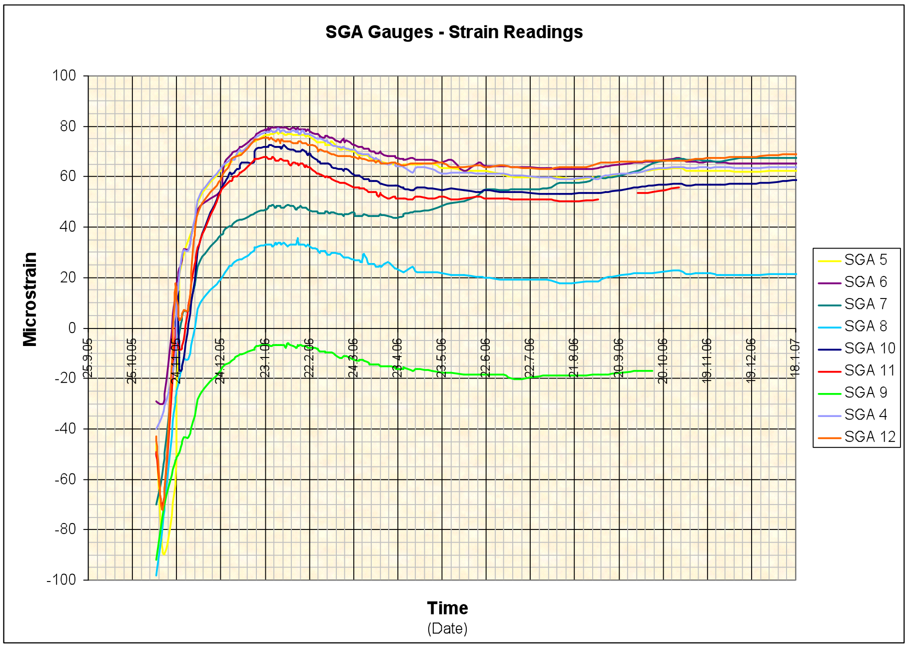

**Figure 8.6: Strain Measured in Upstream-Downstream Direction**

After the evident expansion strain relaxation of approximately 15 microstrain, the net effective expansivity corresponded more closely to the 7.1 x $10^{-6}/^{o}C$ measured for the Çine RCC in the laboratory.

### 8.3.4. WADI DAYQAH DAM

The RCC of Wadi Dayqah Dam was a lean mix, low strength material that did not perform, or behave as well as the RCCs of Wolwedans, Knellpoort, or Çine. While the precise performance of the RCC will never be known with any certainty and some significantly different behaviour was evident at the two separate levels instrumented, some shrinkage/creep could be determined in the instrument data.

In the case of Wadi Dayqah Dam, with core temperatures sustained at their hydration peak (see **Figures 8.7**), compressions gradually relaxed and tensions developed across the majority of the induced joints (see **Figure 8.8**). It is considered that the observed behaviour can be attributed to two factors; the fact that the gauges were installed into RCC that had reached its peak hydration temperature and was then cooled by the superposition of artificially chilled RCC, which subsequently expanded when warmed by the concrete hydration process and secondly, that some drying shrinkage and creep were probably experienced in the lean RCC, which contained a very high content of non-cementitious fines and aggregates with a very high moisture absorption.

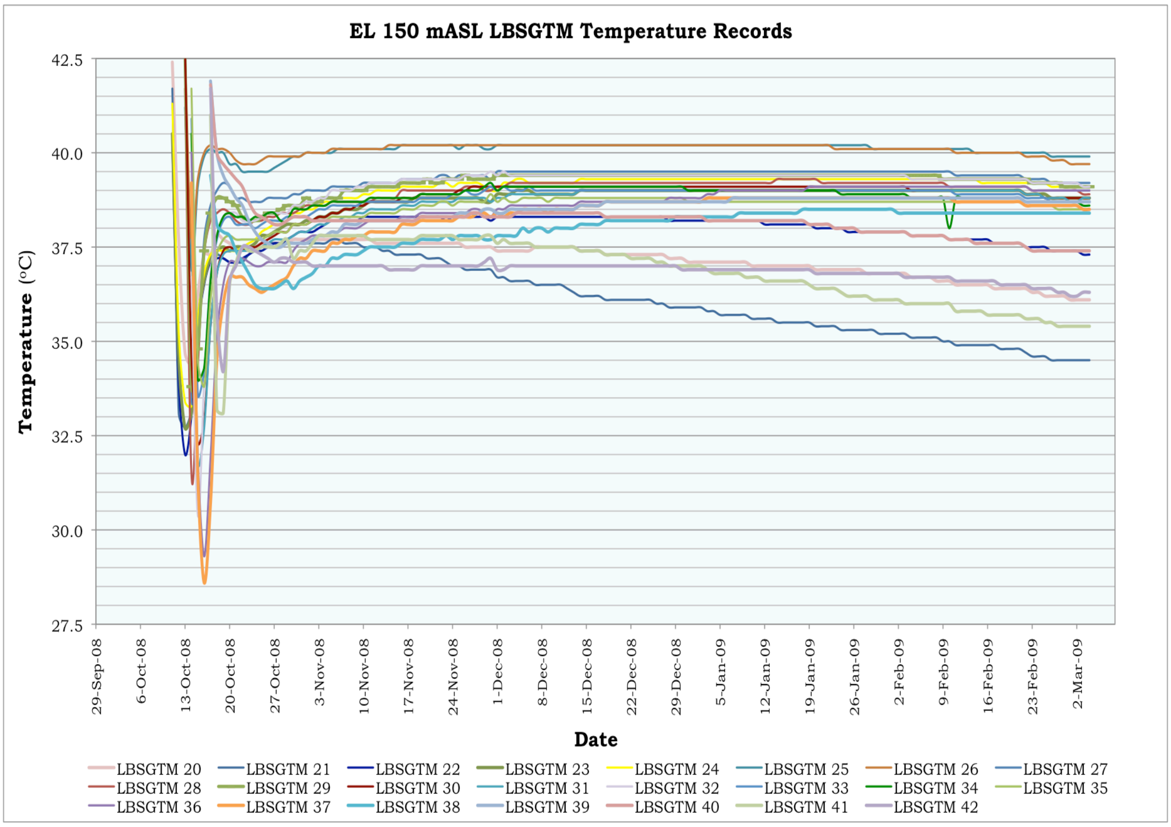

**Figure 8.7: Typical Temperature History for Wadi Dayqah Dam**

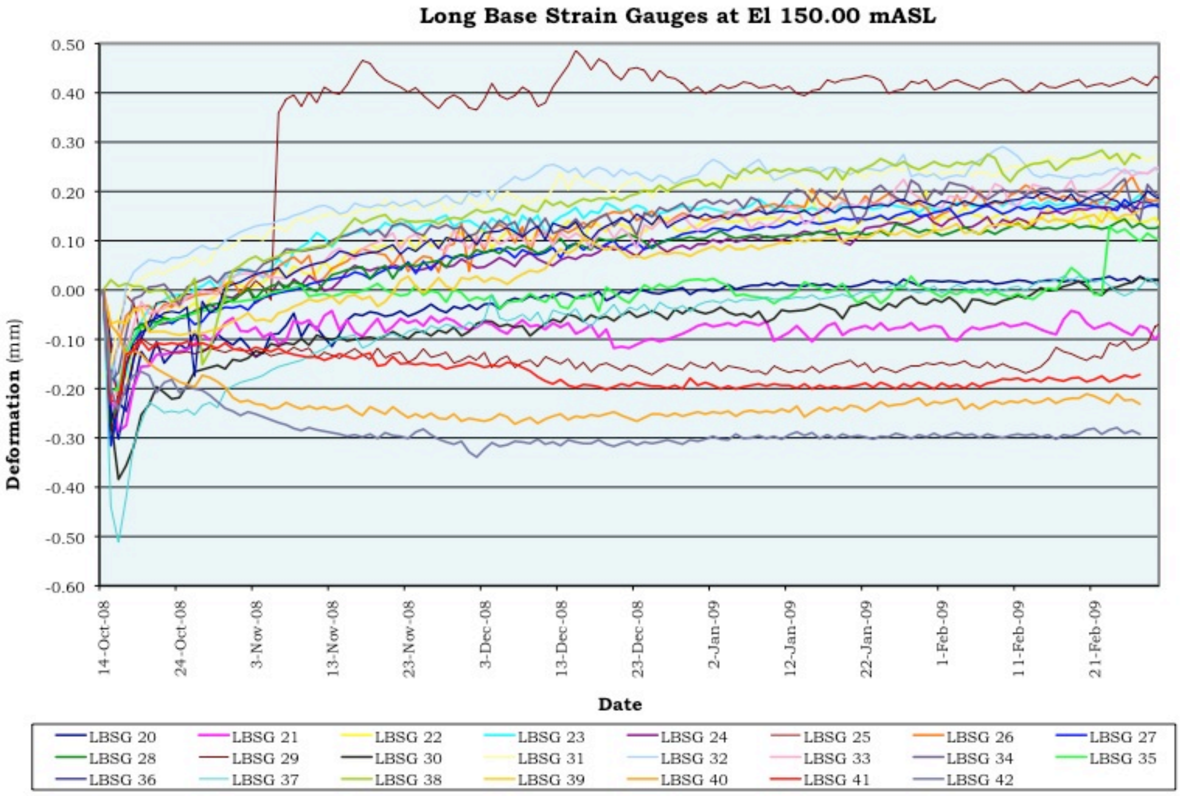

**Figure 8.8: Typical Induced Joint Displacement for Wadi Dayqah Dam**

A further paradox was observed in a complete disparity in the strain measured in the two separate levels of instrumentation installed. The strain measured in the second level of instrumentation, just 15 m above the first, was less than 30% of that measured on the instrumentation in the level below.

The Wadi Dayqah Dam RCC contained a high proportion of fine aggregates, a high content of non-cementitious fines and a high w/c ratio. The aggregate quality, shape and surface texture may also not have been ideal. Accordingly, all of the factors that are likely to increase shrinkage and creep in concrete were evident in the RCC at Wadi Dayqah Dam and despite this fact, the shrinkage measured was significantly less than that typically expected in CVC. As a consequence of the continued development of shrinkage after the RCC was experiencing tension, it is considered most likely that its primary origin lies in autogenous and drying shrinkage, as opposed to creep under stress.

### 8.3.5. CHANGUINOLA 1 DAM

At the time of writing, approximately one third of the RCC had been placed at Changuinola 1 Dam in Panama and while the first level of instrumentation had been installed, the data record was insufficient to provide any opportunity for useful analysis. A single strain gauge, however, was installed perpendicular to the dam axis directly into the high-workability, high-paste RCC during the initial placement and over six months of measurement was available for review. The associated record indicated almost identical behaviour to that from similar gauges at Çine Dam, with an initial linear thermal expansion reducing by approximately 12% over the first few months to reflect a consequent expansion proportional to the laboratory-measured coefficient of thermal expansion. Furthermore, cracks were observed in the RCC placement surface, when left exposed for several weeks, suggesting excessive thermal gradients and linear expansion under the hydration temperature rise.

### 8.3.6. SUMMARY

In summary, the above evaluations provided evidence suggesting that the RCC at Wolwedans, Knellpoort and Çine Dams suffered no perceptible autogenous, or drying shrinkage and no creep shrinkage under restrained thermal expansion. While the instrumentation at Çine Dam indicated that some expansion strain relaxation occurred when the RCC thermal expansion was partly unrestrained, the fact that linear thermal expansion was evident in such a massive section of concrete (> 100 m in length), where significant internal restraint would normally be expected to constrain such expansion, was considered surprising. Recording almost identical behaviour in the RCC of Changuinola 1 Dam was considered to provide a significant validation of the apparent resilience of immature high-paste RCC to creep under thermal expansion.

While a quantitative interpretation of the findings at Wadi Dayqah Dam was somewhat more complicated, it is considered that some drying shrinkage must have occurred, quite possibly related to the use of lower quality aggregates. It is, however, considered particularly significant that this behaviour was only determined in the single example of lean RCC reviewed in this study. Although this implies that some additional care must be taken in determining appropriate aggregates for RCC in the case of dam designs that are susceptible to materials shrinkage, it also serves to confirm that similar behaviour would have been observed at Wolwedans, Knellpoort, Çine and Changuinola 1 should any significant drying/autogenous shrinkage, or creep have occurred in the RCC at these dams.

## 8.4. MODELLING THE BEHAVIOUR OF RCC IN LARGE DAMS

### 8.4.1. GENERAL

While the observations made on the basis of the data gathered at the five dams clearly demonstrate that the extent of any shrinkage and creep that might have developed in the RCC during the early hydration heating and cooling cycle is undoubtedly very substantially less than would typically be the case for CVC, it appeared that these effects were in fact negligible, or even completely absent in the cases of Wolwedans and Knellpoort dams. This assertion, however, could not be proved quantitatively through simply reviewing the available data, as the influence of too many potential secondary factors could not be ascertained with any certainty.

As it is currently only realistically possible to measure strain in RCC, the associated stresses could not be determined and, while it was obvious that the induced joint openings were substantially less than the traditional theory would have anticipated, it could not be determined whether significant residual stress was evident between the joints, or whether some joint closure had occurred as a consequence of the 3-dimensional structural deflections in the case of the arch dams.

In view of the comprehensiveness of the instrumentation and monitoring, the availability of data, its three dimensional structural function and the fact that the dam has remained relatively consistently full from 2 years after completion, Wolwedans Dam represented the ideal case for the development of a finite element model and a consequential determination of the behaviour of its constituent materials. Through modelling Wolwedans Dam under hydrostatic and temperature drop loads, it was considered that the behaviour measured on the prototype structure could be reproduced by isolating the actual degree of shrinkage/creep of the RCC that had occurred during the hydration heating and cooling cycle.

The subsequent analyses undertaken, and presented in Chapter 5 and Appendix B, represent the key focus of the investigations for this doctoral research programme. The validity of small-scale laboratory testing of such complex phenomena as shrinkage and creep in RCC will always be questionable, as discussed under section 8.2.3. However, the behaviour of RCC measured on the scale of a prototype dam cannot be denied. Comparing the measured performance with a structural model allows the development of a real understanding of how the material is behaving within the dam. While good comparisons can be made in 2-dimensional structures, comparing modelled and actual performance for a 3-dimensional structure provides a platform on which basis many ambiguities can be removed and consequently meaningful conclusions can be drawn.

The specific value of this work is found in the use of measured performance on a prototype dam to demonstrate with a high level of confidence the actual early shrinkage/creep behaviour of high-paste RCC.

### 8.4.2. STRUCTURAL MODELLING APPROACH

The target reference performance for modelling was taken as the induced joint openings at approximately mid dam height, central crest displacements and displacements at reference points in the upper gallery, as measured on the prototype structure (as illustrated on **Figure 8.11**) during a winter after the heat of hydration had been fully dissipated. While grouting of the induced joints did not impact the behaviour of the structure to any real extent, it was considered that a higher level of confidence would be possible for simulation of the structural behaviour pre-grouting. Using the known materials characteristics of the RCC and the As-built structural geometry, a range of possible shrinkage/creep behaviour characteristics were modelled in an effort to reproduce the measured displacement behaviour of the prototype Wolwedans Dam structure.

With a temperature drop from placement of approximately 8°C at elevation RL 66.25 m by July 1993, total shrinkages from 80 to 380 microstrain were modelled through the imposition of temperature drops of between 8 and 38°C in conjunction with a thermal expansivity for the RCC of $10 \times 10^{-6}$/°C.

A sensitivity analysis was also completed in an effort to establish whether it might be possible to reproduce the measured crest displacements and joint openings with some creep and higher, or lower E modulus values for the dam RCC.

### 8.4.3. PROTOTYPE REFERENCE BEHAVIOUR

Only 3 of the 16 induced joints at mid-height opened at Wolwedans and only these joints were allowed to open on the FE model analysed, as illustrated on **Figure 8.9**.

For displacement reference, survey data recorded twice annually at the beacons located on the non-overspill crest at either side of the spillway (P113 & P120) were used, as illustrated on **Figures 8.10** & **8.11**. The winter displacements recorded in early July 1993, when a temperature drop of approximately 8°C was recorded within the core zones of the dam, were compared with deflections read from the FE model.

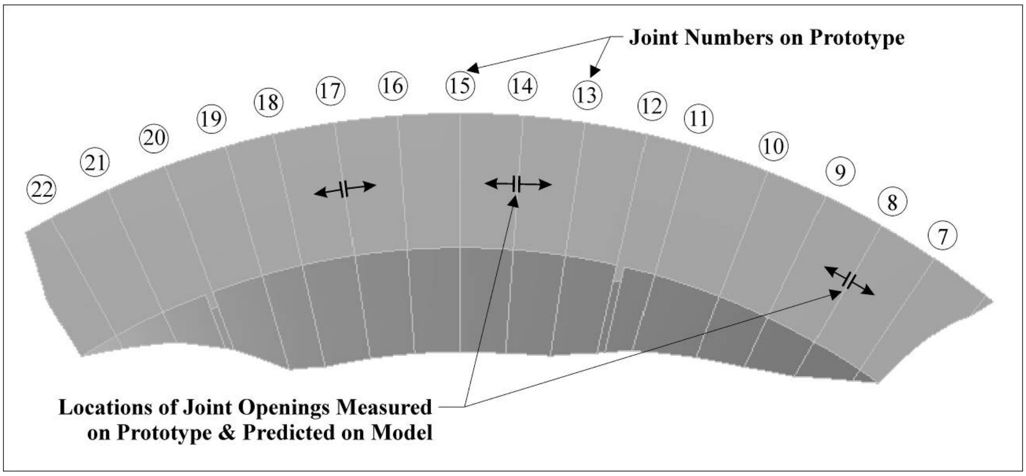

**Figure 8.9: Horizontal Section Illustrating Induced Joints at Mid-Height**

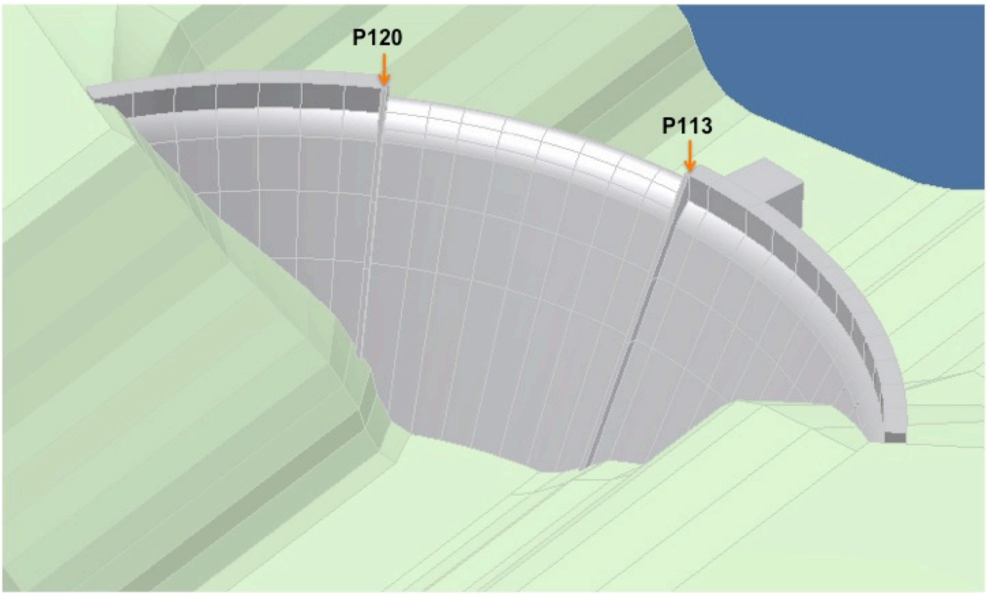

**Figure 8.10: FE Model – Illustrating Crest Displacement Monitoring Points**

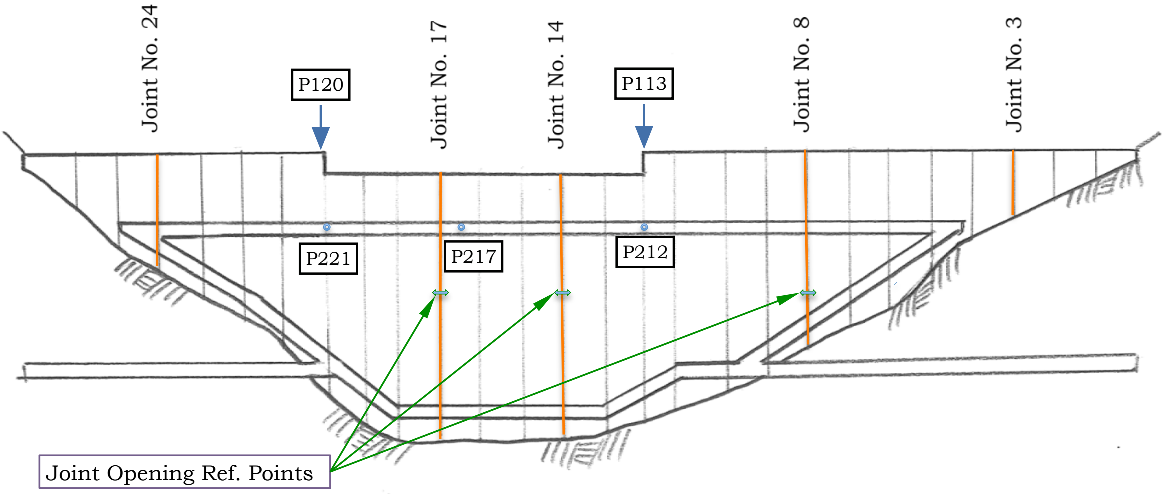

**Figure 8.11: Primary Prototype Structure Behaviour Reference Points**

### 8.4.4. MODELLING RESULTS

As expected, the model demonstrated the joint openings and crest displacements to increase with temperature drop. The stress distribution patterns were also significantly impacted by the applied temperature drops, with increased cantilever action being indicated through the elastic analyses and higher, but more localised arch compression stresses. For an effective temperature drop exceeding 15°C, the indicated level of heel tensions is such that cracking would undoubtedly occur, which in turn would give rise to increased structural displacements. It is consequently considered that the displacements predicted through elastic analysis under-estimate the real situation for the higher temperature drop simulations.

Reviewing the indicated stress patterns, the analyses further demonstrated that some concerns in respect of the structural behaviour would exist should the effective temperature drop be 25°C, or higher. Interestingly, the model also confirmed that the residual stress level between the open joints remained insignificant (< 0.02 MPa).

**Table 8.1** presents a summary of the important predicted displacements and joint openings, compared to those measured at the beginning of July 1993, before the induced joints were grouted.

**Table 8.1: Predicted & Measured Horizontal Displacements & Openings**

| **Scenario** | **Effective Total Temp. Drop** (°C) | **Displacements** (mm) | | | | | **Central Joint Openings** (mm) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | P113 | P120 | P212 | P217 | P221 | Jt. 8 | Jt.14 | Jt.17 | Total |
| **1** | 8 | 12.7 | 8.4 | 8.8 | 10.1 | 6.1 | 1.17 | 0.77 | 1.56 | 3.50 |
| **2** | 8 / 11** | 14.3 | 8.6 | 9.4 | 12.4 | 6.8 | 1.20 | 0.46 | 1.88 | 3.54 |
| **3** | 15 | 18.1 | 10.0 | 11.7 | 14.4 | 7.7 | 4.60 | 2.67 | 4.54 | 11.81 |
| **4** | 25 | 26.1 | 13.2 | 15.1 | 17.3 | 10.9 | 10.16 | 5.58 | 8.51 | 24.25 |
| **5** | 38 | 35.3 | 16.5 | 20.3 | 21.3 | 13.6 | 10.83 | 9.75 | 13.60 | 34.18 |
| Measured July 1993 | | 14.5 | 11.7* | 7.65 | 10.1 | 7.5* | 1.0 | 0.95 | 1.45 | 3.40 |

The figure marked with "*" are those in which a lower level of confidence is considered to exist.

** - Scenario 2 assumed an internal zone temperature drop of 8°C and an external zone temperature drop of 11°C, in line with the findings of Chapter 5.

The sensitivity analysis established that the equivalent measured crest displacements could be reproduced on a model with a higher E modulus and some RCC creep, but such a scenario caused the induced joint openings to be substantially larger than measured on the prototype. Similarly, it was possible to reproduce the measured induced joint openings with a lower RCC E modulus and some creep, but for such a scenario, the crest displacements exceeded those measured.

### 8.4.5. RESULT DISCUSSION AND SUMMARY

Ignoring reference points P120 and P221, it can be seen that a simple, uniform temperature drop of 8°C most closely replicated the displacements and joint openings measured on the prototype dam. Only the higher displacement measured at point P113 would remain unexplained, although it is considered that this reference point is also subject to exaggerated upstream crest movements caused by high summer temperatures within the NOC section of the dam.

On the basis of the analyses completed as part of Chapter 5, the Wolwedans Dam structure is more likely to behave in accordance with Scenario 2 than Scenario 1 and considering the levels of confidence that can realistically be expected for FE modelling of a concrete dam on a variable foundation rockmass, it is suggested that Scenario 2 should be assumed as the most realistic replication of the actual dam behaviour.

With RCC placement temperatures generally varying between 21 and 22°C and with temperatures across the dam section in July 1993 generally between 13 and 14°C, the dam structure can be seen to have experienced a "core" temperature drop from placement of approximately 8°C. Scenarios 1 and 2 accordingly represent situations that would require that the RCC of Wolwedans Dam demonstrated elastic behaviour characteristics right from placement.

### 8.4.6. THERMAL MODELLING OF CHANGUINOLA 1 DAM

Through a detailed thermal analysis, described in Chapter 5, the development of an observed crack in the surface of the RCC placement at Changuinola 1, after several week's exposure, was modelled. Assuming a worse case scenario of no creep in the RCC, the modelling predicted the development of the crack with a high level of accuracy. Adding creep of the order of 25 microstrain was demonstrated to be adequate to substantially eliminate the likelihood of cracking within the first 3 months after placement, indicating strongly that the RCC had therefore in fact exhibited little, or no creep during thermal expansion.

### 8.4.7. CONCLUSIONS

The structural modelling completed as part of the investigations addressed herein clearly demonstrated that the RCC of Wolwedans Dam could not have suffered from any significant shrinkage or creep during the hydration cycle. A similar behaviour was indicated through thermal modelling for the Changuinola 1 Dam. In view of the complexities in defining the elastic and inelastic behaviour of concrete subject to temperature changes and the inherent variability of a foundation rockmass, modelling the performance of a prototype dam structure can only be considered an estimation and accordingly, it cannot be stated with certainty that no shrinkage, or creep occurred in the RCC at Wolwedans Dam. However, it can be stated with certainty that the shrinkage and creep that would be typically assumed for CVC, or RCC did not occur and consequently the traditionally assumed design approach can be seen to be inappropriate.

## 8.5. THE COMPARATIVE COMPOSITION & PROPERTIES OF CVC & RCC

### 8.5.1. GENERAL

Through a literature study, the phenomena of shrinkage and creep in concrete were addressed in detail in Chapter 3.

Shrinkage and creep in concrete are very similar, 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 the composite material 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 skeletal 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.

The better developed the aggregate skeletal structure within concrete, the less the paste shrinkage impacts the overall internal composite structure of the concrete. Essentially, in a concrete with a structure made up of aggregate-to-aggregate contact, the in-filled paste will experience substantially less autogenous shrinkage and be less susceptible to creep than a concrete comprising aggregates suspended in a medium of paste. From a geotechnical point of view, when constrained and before the paste itself has developed strength, the former concrete type will also indicate a substantially greater rigidity than the former.

### 8.5.2. HIGH-PASTE RCC IN LARGE ARCH DAMS

On the basis of a review of the factors that make concrete susceptible to autogenous and drying shrinkage and creep, it becomes apparent that high-paste RCC is perhaps the ideal concrete format in respect of minimising the impacts of shrinkage and creep.

The method of construction and the consequential development of aggregate-to-aggregate contact and a strong aggregate skeletal structure are further considered to represent a significant factor in the creep-resilient nature of high-paste RCC. As discussed in Chapter 6 and illustrated on **Plates 8.1** and **8.2**, the better shaped, continuously graded aggregate, the high aggregate content and the method of compaction together contribute to causing the behaviour of immature high-paste RCC to be influenced more strongly by the aggregate skeletal structure, while the behaviour of immature CVC will be more strongly influenced by the paste.

**Plate 8.1: Typical CVC Core**

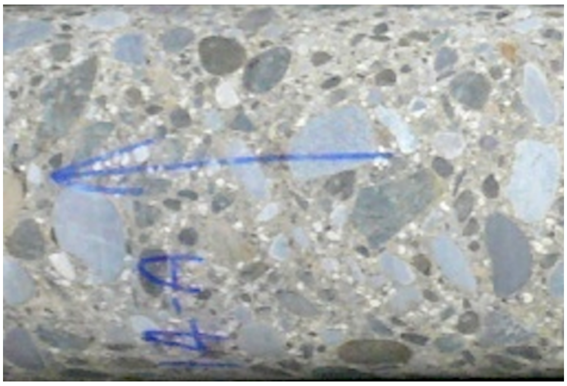

**Plate 8.2: Typical RCC Core**

Furthermore, as described in Chapter 6, a simplified analysis of Wolwedans Dam under the heating action of hydration, without hydrostatic load, indicated that upstream movement of the central crest due to both thermal expansion and gravity caused the containing stresses within the critical upper section of the structure to be eliminated. Bearing in mind the evident ability of high-paste RCC to expand linearly with a temperature rise even under considerable internal restraint, the identified effect would have undoubtedly given rise to unrestrained expansion of the RCC in the crest at Wolwedans under the hydration temperature rise. In the absence of containing stress, stress relaxation creep is no longer a factor and accordingly, this finding provides further motivation to justify the apparent absence of creep in the critical structural elements of Wolwedans Dam. This effect will generally be apparent in the crest of any dam with a curvature and particularly in relatively flexible arch structures.

## 8.6. A NEW UNDERSTANDING OF THE EARLY BEHAVIOUR OF RCC IN LARGE DAMS

### 8.6.1. MOTIVATION

As discussed in Chapter 6, the investigations and analyses completed have demonstrated that a high-paste, high strength RCC mix in an arch structure need not exhibit any significant shrinkage, or creep during the hydration cycle. Lower strength, lean RCCs will indicate some creep, while mixes with less than ideal materials remain susceptible to drying shrinkage and the findings presented relate very specifically to high quality, high-paste RCC.

The strain gauge (SGA gauges) data recorded at Çine Dam and Changuinola 1 Dam are considered of particular importance. The apparent linear thermal expansion evident in a location that would be assumed to be subject to significant internal restraint is considered to provide evidence of a behaviour that is dominated by aggregate-to-aggregate particle contact. The fact that such linear expansion occurs in RCC at such an early age provides further evidence of an inherent early resistance to creep and the likelihood of increased creep resistance in the mature concrete.

As a result of the fact that early shrinkage and creep in concrete are interdependent effects that occur simultaneously during the process of maturation, a realistic separation of the two is not practically possible. Furthermore, the early development of internal shrinkage obviously creates a susceptibility to creep under load. With drying shrinkage in the core of a mass concrete block generally agreed as being negligible, unless related to a specific problem in the aggregates, the important shrinkage is autogenous shrinkage. While the terms 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.

### 8.6.2. DEFINITION OF APPROPRIATE RCC SHRINKAGE AND CREEP BEHAVIOUR

The study has clearly demonstrated that the 125 to 200 microstrain combined shrinkage and creep that is conventionally accepted for an equivalent CVC in a dam during the hydration cycle does not occur to anywhere close to the same extent in high-paste RCC.

For a high-paste, high pozzolan content RCC mix, with well-graded, high quality aggregates in an arch dam, it is undoubtedly possible to produce an RCC with negligible shrinkage and creep.

As a result of an inherent dependence on the nature, grading and the effective compaction of the constituent materials, it is considered essential to treat each set of circumstances for an RCC mix on a case-specific basis and appropriate materials testing should be exhaustive when reliance on a low shrinkage/creep RCC is important to the dam design.

For the preliminary design of a gravity dam constructed with a high quality, high-paste RCC, it is considered appropriate to assume a total shrinkage and creep of approximately 50 microstrain.

The RCC mix for an arch dam will usually be designed for minimum shrinkage and creep and should contain high quality aggregates combined with approximately 200 kg/m$^3$ cementitious materials, of which approximately 70% would be a high quality fly ash. Even in such circumstances, the assumption of a total shrinkage/creep of the order of 20 microstrain should be applied for preliminary design, but verification testing would be required before a definitive reliance could finally be placed on such performance.

In the design analyses for an RCC arch/arch gravity dam, it is considered important to include an evaluation of the anticipated behaviour during construction and the consequential impacts of temperatures elevated by hydration heat.

As the opportunities in respect of the evident better early behaviour of high-paste RCC are investigated, more dams will be appropriately instrumented, more information will be reported and a significantly greater database of RCC shrinkage and creep behaviour will be developed. As such information becomes available, the definition of the associated behaviour of high-paste RCC for dam design will progressively evolve.

### 8.6.3. Key Issue in Respect of RCC Creep Resilience/Improved Early Behaviour

The study demonstrates that there is undoubtedly a specific composition and type of RCC that indicates increased resilience to creep and shrinkage. All examples of negligible shrinkage and creep behaviour relate to "high-paste" RCC and all of the references to high creep relate to a "lean" RCC. A further two factors are common to the low creep/shrinkage RCCs and these are a high fly ash content and total cementitious materials contents approaching, or exceeding 200 kg/m$^3$.

Evaluation of the factors of influence would suggest that the development of a strong aggregate skeletal structure with aggregate-to-aggregate contact is also particularly important and this is best achieved with a high-workability RCC, with high quality, well-graded and well-shaped aggregates, as discussed in Chapter 6.

A high-paste RCC will typically comprise approximately 200 litres/m$^3$ of paste (excluding aggregate fines) and 800 litres/m$^3$ of aggregates and the RCC must be designed volumetrically, with all voids in the aggregates slightly over-filled with lubricating paste that is squeezed up to the surface as the RCC is compacted and a strong aggregate-to-aggregate contact is developed.

The ideal RCC mix composition for maximising resilience to creep might be as follows:

| **Constituents** | Portland Cement | Fly Ash | Water | Coarse Aggregate | Fine Aggregate | Retarder |
|---|---|---|---|---|---|---|
| **By Mass** (kg/m$^3$) | 62 | 143 | 115 | 1400 | 800 | 3.4 |
| **By Volume** (litres/m$^3$) | 20 | 62 | 115 | 500 | 300 | 3 |
| Net Paste (*l*/m$^3$) | Fines (*l*/m$^3$) | Aggregate (*l*/m$^3$) | Paste/ Mortar | Sand/ Aggregate | | |
| 200 | 30 | 800 | 0.40 | 0.375 | | |

In order to minimise the likely impact of creep, it is also considered appropriate to design the dam structure for minimum possible containment stress during the period that peak hydration temperatures are experienced and to design the RCC mix for the lowest possible heat of hydration.

Notwithstanding the above, it is considered necessary to embark on an extensive and case-specific testing and development programme when intending to design an RCC for minimal shrinkage and creep and this should include the construction and instrumentation of a full scale trial.

## 8.7. THE APPLICATION OF THE NEW RCC MATERIALS MODEL

### 8.7.1. THE IMPACT ON DAM DESIGN

In order to develop a meaningful understanding of the implications of the new understanding of the early behaviour of high-paste RCC in large dams, it was considered beneficial to illustrate the consequences of its application, as discussed in Chapter 7.

The most important issues in respect of temperature and the early behaviour of RCC in a dam relate to tension stresses developed as a result of the long-term loss of temperature, as the hydration heat is dissipated. In the case of an RCC gravity dam, these tensions are managed in a direction parallel to the dam axis by including induced transverse contraction joints, which are generally sealed on the upstream face with embedded waterstops. In the case of large gravity dams, however, these tensions can also develop cracking parallel to the dam axis and many examples of such cracking have been observed over the years in South Africa in mass concrete dams.

### 8.7.2. THE IMPACT ON INDUCED JOINT SPACINGS AND OPENINGS

Taking Changuinola 1 Dam in Panama as an example, an analysis clearly illustrated the traditionally accepted method for establishing induced joint spacing and openings to be substantially flawed, whatever RCC behaviour model is assumed. The analysis further demonstrated the unrealistic level of conservatism inherent to applying a traditional RCC materials behaviour model in respect of anticipated induced joint openings.

### 8.7.3. THE IMPACT ON RCC ARCH DAM DESIGN

In the case of an arch dam, a temperature drop load substantially compromises the entire structural function by shrinking the structure to a smaller size than the space that it was constructed to fill, as discussed in **Appendix A**. A mass concrete arch dam is constructed in monolithic blocks that are simply allowed to shrink away from each other, with the gap in between being filled with grout under pressure at a suitably low temperature. Usually, looped pipes are built into the concrete and chilled water is circulated soon after casting in order to draw out the hydration heat and reduce the concrete temperature sufficiently to allow grouting.

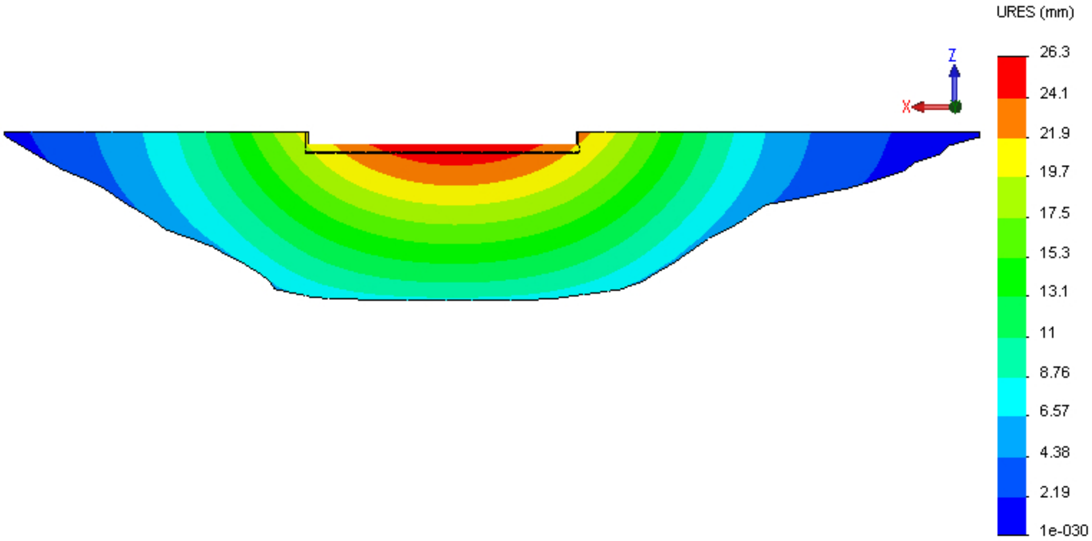

**Figure 8.11:** **Total Horizontal Downstream Displacement for Changuinola 1 Dam with Hydrostatic Load and no Temperature Drop**

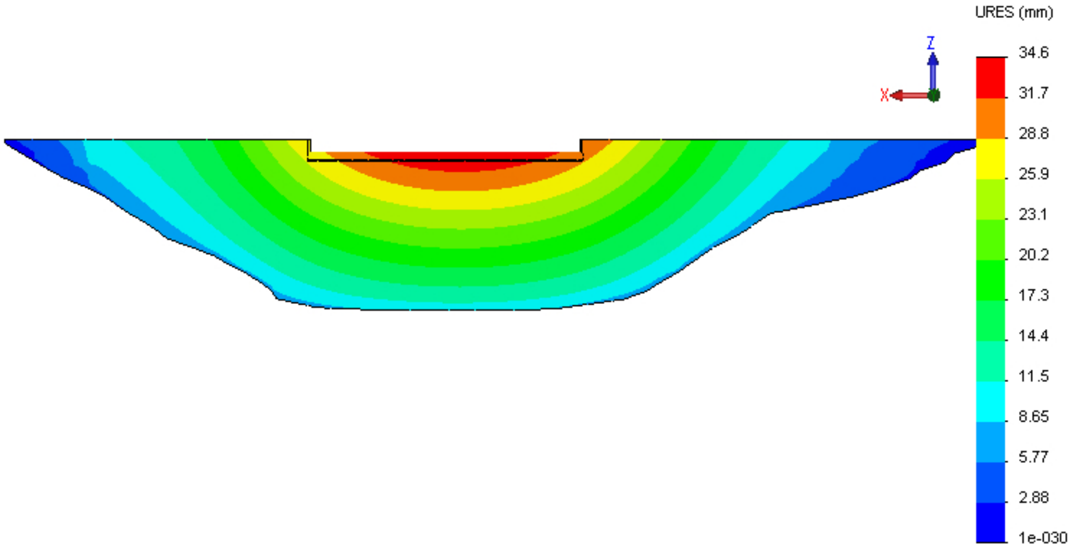

**Figure 8.12:** **Total Horizontal Downstream Displacement for Changuinola 1 Dam with Hydrostatic Load and 6°C Temperature Drop**

In view of the fact that RCC is constructed in horizontal layers, transverse joints are induced, as opposed to being formed, and the installation of looped cooling pipes is rather impractical. Consequently, grouting systems must be installed in the induced joints, while grouting must either be undertaken after the natural cooling process has run its course, or earlier under appropriate pressures, or not at all. With significant pressure commonly to impound as early as possible, very rarely does the opportunity exist to wait to grout the induced contraction joints and it is correspondingly extremely important to understand exactly how the RCC has behaved through the hydration cycle.

The design example of Changuinola 1 Dam in Panama demonstrated that, applying the new understanding of the early behaviour of RCC in a temperate climate, it would be possible to avoid joint grouting in an RCC arch/gravity dam. With the traditional materials model adopted for RCC, this would certainly never be the case. Although the impact of a 6°C temperature drop on the dam structure can be clearly observed in the increased maximum crest displacements illustrated by comparing **Figures 8.11** and **8.12**, critical stresses remain comfortably within acceptable limits.

While the impact of the new understanding of the early behaviour of RCC was demonstrated to be critical in respect or arch-type dams, the situation in respect of gravity dams is simply one of demonstrating the unnecessary conservatism applicable when the traditional RCC materials model is applied. In both cases, however, substantial advantage is perceived in understanding the actual mode of behaviour of RCC as a material. Applying assumptions in dam design, the real situation and the real factors of safety will never be known.

### 8.7.4. THE NEED FOR TESTING

While the investigations and analyses undertaken demonstrated without doubt that RCC in large dams behaves quite differently to CVC during the course of the hydration cycle, the need for as much verification testing of the shrinkage characteristics of each specific RCC mix was recognised.

Depending on the importance of shrinkage and creep in respect of the design of a particular dam, the following testing recommendations were considered appropriate:

- For all significant RCC dams, temperature and strain gauges should be installed and monitored in the RCC of the Full Scale Trial.
- In the case of an RCC arch dam for which materials shrinkage might be problematic, additional laboratory and practical testing of the RCC will be required.

## 8.8. CONCLUSIONS

### 8.8.1. DEFINITIVE FINDINGS

The investigations and analyses presented herein illustrate probably the first publicly documented case whereby the early behaviour of RCC in large dams is validated against a prototype structure, which relies on 3-dimensional arch action for stability.

The findings conclusively prove that the RCC of Wolwedans Dam did not suffer the level of shrinkage and creep that would traditionally have been assumed for RCC, or CVC dam design. Within the level of accuracy realistically possible when modelling a prototype dam structure, it would in fact appear that no perceptible volume reduction, associated with shrinkage and creep during the hydration heat development and dissipation cycle, occurred in the critical structural components at Wolwedans Dam.

While the measured data for Wadi Dayqah Dam demonstrated that drying shrinkage can be experienced in RCC when high w/c ratios, high percentages of non-cementitious fines and poorer quality aggregates are used, the related findings confirm the identified lower creep/shrinkage behaviour as applicable only to high-paste RCC.

### 8.8.2. APPROPRIATE CAUTION IN APPLYING NEW CONCEPTS

While the findings of this investigation are considered definitive, the fact that the new understanding of early RCC behaviour has yet to be broadly tested and explored implies that it should be conservatively applied in the short term. As a result of the study findings, however, it is considered that all full-scale RCC construction trials should include temperature and strain measurement instrumentation specifically designed and configured to develop an understanding of the shrinkage and creep characteristics of the specific RCC to be used. This data should be supported with adequate laboratory testing specifically of the shrinkage characteristics of all of the aggregates to be used.

### 8.8.3. THE NEED FOR CONTINUED OBSERVATION

The conclusions presented are based on instrumentation data from prototype dam structures. The comprehensive data recorded at Wolwedans Dam was sufficient to allow a definitive replication of the actual dam behaviour through Finite Element modelling. Until now, it has only been possible to point towards apparent differences between the early behaviour of RCC and CVC, on the basis of observation, and to try to evaluate this through laboratory testing of inadequately sized and unrealistically manufactured samples.

The limited instrumentation installed in Wadi Dayqah Dam implies that the precise early behaviour of the RCC will probably never be known and accordingly, an important opportunity to increase knowledge of RCC has been lost. The value of the instrumentation installed at Wolwedans, Knellpoort and Çine Dams cannot be overstated and with the knowledge gained, the instrumentation installed in future RCC dams can be improved and more accurately targeted towards the particular measurement of specific phenomena.

The value of the findings of these investigations have been demonstrated, but it is important to continue to gather data on which basis greater levels of confidence can be developed in the new understanding of high-paste RCC behaviour, which will in turn allow greater consequential benefit in terms of economic and safe dam designs. Accordingly, it is strongly advocated that all future RCC dams be appropriately and intelligently instrumented.

## 8.9. RECOMMENDATIONS FOR CONSEQUENTIAL RESEARCH & DEVELOPMENT

It is considered of specific importance that the investigations addressed in this Thesis represent the first published work to evaluate the behaviour of RCC through a comparison of modelled and measured prototype performance. Admittedly, such an analysis is only specifically applicable in the case of an RCC arch dam and there are not yet a significant number of dams of this type that have been constructed around the world. It is also considered of specific importance that most laboratory testing for creep and shrinkage to date has related to lean mix RCC.

In order to ensure maximum benefit is gained from the findings presented in this study, ongoing verification on future RCC dam projects will require laboratory testing, structural modelling and detailed site instrumentation. Only through the repetition of the modelling and prototype comparisons presented herein, can levels of confidence in the early behaviour of all types of RCC be effectively increased.