University of Pretoria

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PhD Thesis:

A New Understanding of the Early Behaviour of Roller Compacted Concrete in Large Dams

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A NEW UNDERSTANDING OF THE EARLY BEHAVIOUR OF ROLLER COMPACTED CONCRETE IN LARGE DAMS

by

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Submitted in partial fulfilment of the requirements for the degree of Philosophiae Doctor (Civil Engineering) in the Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Pretoria.

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Key Terms: Roller compacted concrete (RCC), early behaviour, hydration cycle, thermal effects, autogenous shrinkage, drying shrinkage, stress relaxation creep, dams, arch dams, finite element analysis, instrumentation.

Summary

In respect of autogenous and drying shrinkage and the effects of relaxation creep during the hydration cycle, roller compacted concrete in dams has to date been universally assumed to behave in the same manner as conventional mass concrete,

despite notional evidence to the contrary on prototype dam structures, particularly in respect of high-paste RCC.

While the results of laboratory materials testing and associated early behaviour analyses for RCC have been published, no conclusive example exists in the public domain whereby predicted behaviour is confirmed through measured behaviour on a comprehensively-instrumented prototype dam structure.

In his PhD thesis, Quentin Shaw presents evidence to indicate that the early behaviour of RCC, and particularly high quality, high-paste RCC in dams, is quite different to that of CVC. Referring to instrumentation records from Wolwedans and Knellpoort dams in South Africa, Çine Dam in Turkey, Wadi Dayqah Dam in Oman and Changuinola 1 Dam in Panama, indications of less than expected shrinkage and stress relaxation creep during the hydration cycle in the constituent RCC are documented.

Taking the comprehensively-instrumented and monitored Wolwedans Dam, the actual materials behaviour of the constituent RCC is evaluated through the replication of the prototype behaviour on a finite element model. Through this analysis, it is clearly demonstrated that the level of shrinkage and stress relaxation creep that would be traditionally assumed in RCC simply did not occur. In fact, the analyses suggested that no shrinkage, or creep was apparent.

The reasons for the different behaviour of high-paste RCC compared to CVC are subsequently explored. With Wadi Dayqah Dam as the only example evaluated where some drying shrinkage and/or stress relaxation creep was obviously apparent, the evident susceptibility of this lean RCC mix, with a high w/c ratio, a high content of non-cementitious fines, natural gravel aggregates, a high aggregate water absorption and placement in a very dry environment, is noted. However, it is considered to be the combination of a strong aggregate skeletal structure developed through roller compaction and a low w/c ratio that results in a particularly resilience in high-paste RCC to early shrinkage and creep. It is also recognised that temperature and gravity effects in an arch dam structure will tend to limit, or even eliminate containment stresses in the critical load-carrying upper section and that this will reduce the risk and impact of stress relaxation creep.

Consequently, a new understanding of the early behaviour of RCC in large dams is presented, suggesting that a high quality RCC mix in an arch dam can be designed for a cumulative shrinkage and stress relaxation creep under the hydration cycle of

approximately 20 microstrain, compared with a more traditionally accepted value of between 125 and 200 microstrain.

The implications of these findings on the design of large RCC dams are demonstrated to be significant, particularly in respect of RCC arch dams. In addition, suggestions are made for the requirements in respect of RCC mix design for negligible shrinkage and creep, while an approach to combine the use of field measurement with structural modelling to predict and demonstrate actual RCC behaviour is briefly discussed.

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List of Abbreviations and Acronyms

CBD	Compacted Bulk Density
CVC	Conventional Vibrated Concrete (Mass Concrete compacted with an immersion vibrator)
COSMOS	COSMOS Finite Element Analysis Computer Software
E	Elastic (or deformation) Modulus
FE	Finite Element
FSL	Full Supply Level
H	Height (m)
High-Paste RCC	RCC Containing > 150 kg/m^3 cementitious materials
ICOLD	International Commission on Large Dams
LBSGTM	Long-Base-Strain-Gauge-Temperature-Meter
Lean RCC	RCC Containing < 100 kg/m^3 cementitious materials
mASL	m Above Mean Sea Level
NOC	Non Overspill Crest
RCC	Roller Compacted Concrete
RL	Reduced Level (m)
RMC	Rubble Masonry Concrete
SANCOLD	South African National Committee on Large Dams
Temperatures:	
T1	Concrete Placement (°C)
T2	Maximum Hydration Temperature (°C)
T3	Natural Closure, or Zero Stress Temperature (°C)
T4	Minimum long-term Equilibrium Temperature (°C)
USACE	United States Army Corps of Engineers
USBR	United States Department of the Interior. Bureau of Reclamation
Ø	Angle of internal friction

Stress Sign Convention:

-ve = Compression

+ve = Tension

TERMINOLOGY:

Axis

The "Axis" of a dam is taken as a line parallel to the upstream face. Induced Joints in an RCC dam are inserted on an alignment perpendicular to the axis.

Conventional Analysis Techniques

"Conventional Analysis Techniques" refers to the design approach generally accepted as state of the art practice and adopted by dam engineers worldwide.

Creep

According to Fulton's *Concrete Technology* (9th Edition). 2009[1], "Creep is defined as the time-dependent increase in strain of a solid body under constant stress. Creep may also be manifested as a relaxation of stress under constant strain." In respect of the behaviour of RCC under early heat development and dissipation, it is the latter "relaxation" form of Creep to which the text of this work refers.

Early Behaviour

"Early Behaviour" is taken to mean the shrinkage/creep behaviour that occurs after placement and before the hydration heat is fully dissipated and gives rise to an effective volume reduction in the RCC. In a dam, the hydration heat can take several years to fully dissipate and consequently an evaluation of the impact of the "Early Behaviour" is often only possible on a prototype dam after a substantial delay, but the significant part of this behaviour undoubtedly occurs during the first month, or two after placement, before the concrete has gained significant strength.

Materials Model

In this Thesis, the term "materials model" is taken as the definition of expected materials properties and behaviour for RCC as a construction material.

"New" RCC materials model is an abbreviation occasionally applied for the New Understanding of the Early Behaviour of RCC.

"Traditional RCC Materials Model" describes the assumed behaviour for RCC generally accepted for RCC to date by designers.

Zones: Surface (External) & Core

Figure 7.1 of the USBR's *Design of Arch Dams.* 1977[2] indicates that seasonal temperature variations experienced in a mass concrete (CVC) block will be reduced to 10% at a depth of 2.4 m and 1% at a depth of 24 m, compared to the variations experienced on the surface. For the purposes of this Thesis, the terms "surface", or "external" zone is accordingly used to describe the concrete within approximately 2 to 3 m of the external/exposed surface. The "core" zone consequently refers to all concrete at greater depth than the "surface" zone. Occasionally, reference is made to an "intermediate" zone and this is defined as the concrete between 2.5 and 5 m from the external surface.