STATE OF THE ART IN ROLLER COMPACTED CONCRETE (RCC) DAMS: DESIGN AND CONSTRUCTION

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ABSTRACT

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Roller Compacted Concrete (RCC) appeared as a feasible new type of construction material for concrete gravity dams. RCC became very popular rapidly all over the world due to its low cost and fast deployment and is used for various purposes, including the construction of new dams, pavements, highways and the rehabilitation of existing dams. The primary purpose of this study is to investigate wide range of practice in RCC dam construction with a focus on the material properties. The material properties of a range of RCC dams around the world are documented with the goal of determining the factors affecting critical design attributes of RCC dams. As a secondary note, the analyses methods for the structural design and evaluation of RCC dams are investigated. The current literature on the evaluation of these dams was surveyed given. Finally, the text also includes some information on the performance of a range of RCC dams around the world and the accompanying recommendations for good performance.

Keywords: roller compacted concrete, seismic analysis of RCC dam, thermal crack, strength of RCC, mixture design.

ÖZ

SİLİNDİRLE SIKIŞTIRILMIŞ BETON (SSB) BARAJLAR ÜZERİNE EN SON TEKNOLOJİK GELİŞMELER: DİZAYN VE YAPIM

Söğüt, Serdar
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Şubat 2014, 210 sayfa

Silindirle Sıkıştırılmış Beton (SSB) son zamanlarda beton ağırlık barajlar için uygulanabilir yeni bir yapım malzemesi olarak ortaya çıkmıştır. SSB düşük maliyeti ve hızlı yerleştirilmesi sebebiyle tüm dünyada popüler olmuş olup, yeni barajların yapımı, eski barajların rehabilitasyonu ve yol yapımı gibi çeşitli alanlarda kullanılmaktadır. Bu çalışmada öncelikli olarak dünyadaki geniş SSB baraj pratiğinin malzeme özelliklerine odaklı olarak incelenmesi hedeflenmiştir. Değişik şartlarda yapılan barajlarda elde edilmiş olan malzeme özellikleri tasarım kriterlerini etkileyen parametrelerin belirlenmesi amacı ile sunulmuştur. Bu tezin ikincil amacı ise SSB barajların yapısal açıdan tahkiki için kullanılan analiz metodlarının incelenmesidir. SSB barajların tahkiki için kullanılan analiz teknikleri araştırılmıştır. Son olarak, bu tezde çeşitli SSB barajların performansı üzerine bilgi verilmekte, bu örneklerden yararlanarak bu sistemlerde beklenen performansın elde edilmesi için gerekli öneriler sunulmaktadır.

Anahtar kelimeler: silindirle sıkıştırılmış beton, SSB barajın sismik analizi, termal çatlama, SSB dayanımı, karışım tasarımı.

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To My Dear Family

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LIST OF ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CMC	Conventional Mass Concrete
CVC	Conventional Vibrated Concrete
FEM	Finite Element Method
ICOLD	International Commission of Large Dams
NMSA	Nominal Maximum Size of Aggregate
PCA	Portland Cement Association
PGA	Peak Ground Acceleration
RCC	Roller Compacted Concrete
RCD	Roller Compacted Dam
USACE	United States Army Corps of Engineers

CHAPTER 1

INTRODUCTION

1.1 Definition and Background

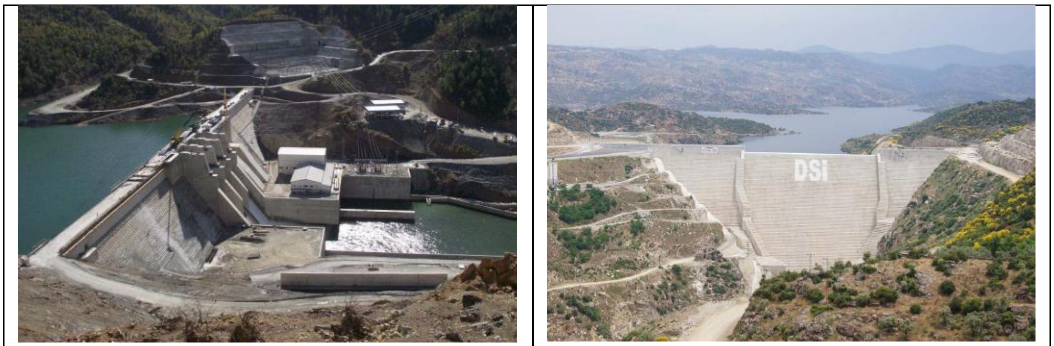
Roller Compacted Concrete (RCC) appeared as a feasible type of concrete four decades ago. RCC became very popular rapidly all over the world due to its low cost and fast deployment during dam construction. Having zero slump distinguishes RCC from conventionally vibrated concrete (CVC). RCC is used for various areas of construction like new dams, rehabilitation of existing dams, pavements and highways.

RCC is a concrete which is compacted by vibratory roller and is able to sustain loads during compaction process. Physically, it seems like asphalt mixture. RCC can be seen as combination of earth material and CVC when its mechanical properties are investigated. It resembles CVC due to its strength gain, performance and elastic properties. On the other hand, permeability, durability and placing methods of RCC show parallel behavior with earth and rock fill materials.

RCC dams emerged with efforts of both structural and materials engineers. From 1950s to 1980s, popularity of gravity concrete dams declined because of the fact that they were costly to be constructed in wide valley sites.

In these years, embankment dams were preferred to concrete gravity dams due to their low cost [2][3]. However, despite their economical advantages, embankment dams were more prone to damage and failure. In 1960s, structural and materials engineers tried to combine advantages of concrete gravity dam and embankment dam to handle safety and financial problems. During the 1970s, some laboratory tests and field demonstrations were conducted using RCC. In 1974, repairing of the diversion tunnel and rehabilitation of the auxiliary and service spillways of Tarbela Dam was done using RCC showing fast placement characteristic of the material (American Concrete Institute (ACI) 207.5R-99) These studies led to the construction of the first RCC dams, Willow Creek Dam,1982 in the United States and Shimajigawa Dam,1981 in Japan. Construction of these two dams held light to new RCC dams which gained wide acceptance around the world. Figure 1-1 shows the Menge and Çine RCC Dams constructed in Turkey.

In terms of the amount of the cementitious material used in construction, RCC dams can be classified in 3 categories: Lean RCC dams (i.e. hardfill dams) have less than 100 kg/m^3 cementitious material in their mix design. The mixture content of the medium paste RCC dams include between 100-149 kg/m^3 of cementitious material. Dams with cementitious content more than 150 kg/m^3 cementitious material are called hard paste RCC dams.



a)Menge Dam | b)Cine Dam

Figure 1-1 Two RCC Dams in Turkey [114]

A short summary of the advantages of RCC construction and the construction procedure is presented below.

1.2 Advantages and Disadvantages of Roller Compacted Concrete

There are many advantages of RCC dams in concrete technology. Low unit price of RCC materials, flexible ratio of the mixture contents and high construction speed make RCC dams a valuable alternative for different dam projects. On the other hand, what is advantageous for one project may not be the same for another. It is very difficult to generalize design, mixture and construction method for all projects. Given a wrong decision in an aspect of the project, RCC dam may be more costly than the conventional mass concrete (CMC) or the embankment dam. Therefore each project should be evaluated on its own. When the conditions allow consideration of a RCC dam alternative, the following points can be a plus.

1.2.1 Cost

The main advantage of RCC dams is the cost savings. Construction cost histories of RCC and CMC show that the unit cost per cubic meter of RCC is considerably less than CMC. The percentage of saving with RCC depends on availability and cost of the cement and aggregate and the total quantity of concrete. Moreover, the reduced cementitious content and the ease of placement and compaction leads RCC dams to be built in more economical way. A big advantage of RCC dams compared to the embankment dams comes from constructing the spillway into the dam body rather than having separate excavation and structure. However, the lack of quantity and availability of aggregate and pozzolan near project site is the major drawback for RCC dams against embankment dams [1]. To achieve maximum saving against CMC and embankment dams, RCC dams should be constructed considering following points;

- RCC should be placed as quickly as possible
- More than one design mixtures should be avoided if possible that tend to slow production
- Design should not have extraordinary construction procedures that breaks continuity in construction

Comparison between the cost of RCC dam projects is the other issue. However, it is not actually very simple to determine final actual cost data for making comparison between the costs of RCC dam projects because, the work and materials included in the costs can be exclusive (e.g. mobilization, joints, engineering, facing, diversion, spillway, galleries, foundation) so that only very basic costs of RCC production are usually included in the analysis.

1.2.2 Speed of Construction

The next advantage of the RCC dams is the speed of construction. It results in three main advantages, namely, early operation of the facility, reduced risk of flooding and the corresponding minimized requirements for the diversion structures and cofferdams [4]. The extra profit from earlier completion and water storage can be a big income especially for large RCC projects. Besides that, when a project is completed before the estimated schedule, interest payments for financial credit can also be great.

1.2.3 Equipment and Material

The equipment required for an RCC project is usually mixers, conveyors, trucks, compacters and vibratory rollers. Materials used in RCC design mixture can easily be obtained dependent on the site conditions: proximity of well-quality gravel is extremely important for low-cost construction. For example, given the poor quality aggregates near the site, the original mix design for the Conception, Mujib Dam and the Burnett River Dams had to be changed in order to maintain the mixture strength [2].

1.3 Construction Sequence

RCC placement should be as fast and continuous as possible in order to maintain structural integrity and high joint quality. For this reason, any problem faced in the placing area should be solved promptly. Since there are no alternative monolith blocks to continue the placement of RCC, work can not progress properly in any problem. Preparation and transportation of the material and bedding mortar, fueling, formwork, treatment of the lift surface and assembly of embedded parts should be integrable to the RCC placement rate [4].

1.3.1 Aggregate Production and Concrete Plant Location

Aggregate stockpiles location is very important for RCC dam construction. Generally, massive stockpiles are provided before starting RCC placement. By doing this, huge amount of aggregate is produced during the winter and they are stockpiled cold for use during hot seasons.

Therefore, temperature rise within the dam monolith can be kept low after RCC placement. Adequate loaders or conveyor systems may be equipped to load aggregate efficiently and safely.

The concrete plant location should be chosen to minimize transportation cost and save time. Location of the plant should be kept close to the dam body and in high elevation to minimize distance for conveying or hauling concrete and take the waste material and wash water drain away of the construction area.

1.3.2 Mixing

Mixing is the key process to achieve the desired RCC quality and consistency. Drum mixers and continuous mixers are used to produce RCC. Drum mixers are generally used for small projects because the RCC production rate is low and requires less power than continuous mixers but it is inadequate for mass concrete placements. Continuous mixers are advantageous for large scale projects since their production rate is relatively high and they may contain higher nominal maximum size of aggregates (NMSA). While 25 mm NMSA is allowable for drum mixers, NMSA of up to 100 mm can be used for continuous mixers.

1.3.3 Transporting and Placing

Dump trucks, conveyors or a combination of both are used for transporting the RCC from mixing plant to the placement area [1][5]. The RCC transportation equipments should be capable of transporting the material quickly, without increasing segregation or reducing workability. The allowable time between the start of mixing and completion of compaction should be within 45 minutes.

For windy weather and low humidity conditions, this time is reduced. The volume of the material to be placed in a cycle, access to the placement area and design parameters play an important role in selecting the transportation method. Figure 1-2 shows placement and compaction of RCC from Menge Dam in Turkey.

	
a)placement of RCC	b)compaction of RCC

Figure 1-2 RCC Placement and Compaction in Menge Dam

1.3.4 Compaction

The compaction of RCC is done by vibratory steel drum rollers. Rubber-tire rollers are also used as a final pass to remove surface cracks and tears and provide smooth surface. Compaction of RCC should be started after the placement and finished within 15 minutes. Delays in compaction cause loss of strength and consistency. Each RCC mixture has its own characteristic behavior for compaction depending on the environmental conditions and material types. The appearance of fully compacted concrete is dependent on the mixture content. Generally four to six passes of a dual drum 10-ton vibratory roller achieves the desired density of 98% for RCC lifts between 150 and 300 mm [1] [2].

1.4 Purpose and Limitations

The primary purpose of this study is to gain an understanding of the mechanical properties of the RCC material and the affecting factors based on a wide literature survey on the RCC construction around the world. In contrast to CMC dams, the use of different materials, construction types and project specific practices lead to a wide range of properties for RCC materials. Given the specific problems of RCC dam construction and performance, in addition to the abovementioned study, a literature survey on the stress and thermal analysis of RCC dams are conducted in order to understand the design philosophy of RCC dams clearly.

The focus of this thesis is limited to RCC dams. Therefore, the literature survey was not intended to cover the mechanical properties or analyses methods for conventional, mass concrete gravity dams. However, the foundation of the structural analyses for these systems is common: therefore, some overlap in the analyses method sections is inevitable. The list of RCC dams including information about them is given in Appendix A Table A.1.

1.5 Scope of the Thesis

This thesis is composed of four chapters. Chapter 1 gives an introduction, then states the advantages and disadvantages of RCC, construction techniques, purpose and limitations and finally the scope of the thesis.

In Chapter 2, a literature survey about the design and analysis methods of RCC dams are presented. Two types of analysis, namely, the seismic and thermal analysis are primarily covered. Some other analysis methods applied to the design or assessment of structural or any case specific problems for RCC dams are also presented in the survey.

In Chapter 3, a literature survey on the mechanical properties of the RCC dams is presented. Influence of the mixture proportioning as well as the specific mixture ingredients on the mechanical properties are investigated. The chapter includes a compilation of a wide-range data from dam projects all over the world, showing the wide-range of experience with the RCC material and a mix design study.

Finally, the conclusions and recommendations for future studies are given in Chapter 4.

CHAPTER 2

LITERATURE SURVEY ON DESIGN AND ANALYSIS OF ROLLER COMPACTED CONCRETE DAMS

2.1 Seismic Analysis

2.1.1 Design Considerations

RCC dams are classified within the gravity type of dams and their seismic behavior can be investigated in a similar fashion to CMC systems. However, the concerns in the seismic design of the RCC dams differ from the CMC systems because of the particular construction method for RCC dams. In CMC dams, lift joints are spaced at two to three meters and may not necessarily be horizontal due to staggered construction of concrete blocks so that the joint discontinuity can lead inclined cracks from the upstream to downstream face of a dam. Both sliding and overturning stability problems may be seen. For a RCC dam, horizontal cracking along the lift joints is the major seismic design concern, as these systems are comprised of very thin lift joints that have less tensile strength than the parent concrete. [105][106].

The static initial loads considered in the earthquake analysis are reservoir and tail water hydrostatic force, backfill and silt active pressures and the weight of the dam. The dynamic loads are the inertial loading due to the ground motion acceleration, hydrodynamic loads from the reservoir-dam-foundation interaction, and the dynamic loads to the silt or other backfills.

There are several factors that affect the dynamic response of RCC dams significantly.

1) *Ground Motion Characteristics* directly affects the dynamic analysis because the exceedance of stress limits as well as the duration of this exceedance are deemed critical for such massive concrete structures,

2) *Damping* ratio due to reservoir-dam interaction and especially the dam-foundation interaction affects the seismic demand on the structure significantly. Effective viscous damping ratio combining the viscous damping ratio with the material and radiation sources is proposed by Chopra and Fenves [107],

3) *Foundation modulus* leads to significant changes in the dam stresses, load pattern and the radiation damping,

4) *Hydrodynamic load* affects the dynamic response by causing dam-reservoir interaction. The dynamic properties of the system are changed due to the interaction between the reservoir and the dam body, affecting the modal frequencies, shapes and the damping ratio for varying reservoir levels,

5) *Reservoir bottom absorption* plays a role in response of the dam due to absorption of the hydrodynamic pressure waves at the reservoir bottom.

It is expressed by wave reflection coefficient, such as the formulation given in Chopra and Fenves [107].

2.1.2 Methods of Analysis

The assessment and design of RCC dams for seismic loading can be performed using linear elastic and non-linear analyses tools. Linear analyses tools include simplified analyses (as given in Chopra [107]) using response spectrum methods and linear time history analyses. Nonlinear analyses tools would require time history data, and the required material properties which are considerably harder to obtain compared to linear analyses.

The common analyses method for dams have been linear 2D analyses due to the robust tools developed for the consideration of the soil-structure-reservoir interaction effects in 2D frequency domain. However, it should not be forgotten that the project requirements, as well as the geometry of the structure and seismicity of the project site should be considered before choosing the analysis methodology, regardless of the past experience or the computational tools available. The analyses methodologies commonly used for the design and assessment of RCC dams will be explained in the following sections in more detail.

2.1.2.1 Linear Elastic Analysis

The linear elastic analysis is the simplest tool to evaluate the seismic behavior of RCC dams. The stresses observed on the structure are compared to the selected design limits in order to determine the performance of the structure.

The response spectrum method and the time history analysis are used in linear elastic earthquake analysis. The seismic hazard at a site is usually defined by a design response spectra scaled to peak ground acceleration (PGA) for “Operation Based Earthquake (OBE)” and “Maximum Design Earthquake (MDE)” design earthquakes. In the OBE event, the dam should not go through any serious damage. Only minor cracking is acceptable for this performance level. The maximum tensile stress should not exceed the dynamic tensile strength of the lift joints and the parent concrete. The system should be able to operate without any interruption in its functions. For the MDE level event, cracks may occur on the system and the dam may not be functional anymore due to deformations at the joints and cracking. However, the stability of dam must be ensured.

The time history analysis method is used when further evaluation into the seismic behavior beyond that provided by the response spectrum analysis is needed. It provides the information on the duration of the exceedance of stresses above the allowable limits in contrast to the response spectrum analysis. The method given in USACE-EM-1110-2-6051 [117] uses the duration of these stress excursions to calculate the demand-capacity ratio (DCR). Then, the cumulative duration versus DCR curve is plotted and compared with the limits. The nonlinear time history analysis is required if the demand on the system is above the prescribed limit.

General purpose finite element analysis software are usually preferred for the dynamic analyses of dams. However, the general purpose FE codes do not contain the specific formulation for the modeling of soil-structure-reservoir interaction exactly in the frequency domain. The methodology for solving the problem exactly, as provided in (Chopra and Fenves [107]), is implemented in the code EAGD-84 specifically prepared for the analyses and evaluation of gravity dams in a 2D setting.

The dynamic analyses of an RCC dam using EAGD-84 is presented by Monteiro and Barros [108].

The 52 m high gravity dam in Portugal is analyzed with the design earthquake having a return period of 1000 years and a peak acceleration of 0.5g. Maximum compressive and tensile stresses are observed at the toes and heels as expected. The tensile stress capacity of the elements are exceeded instantaneously only four times within the ground motion leading the authors to conclude that any instability or failure of the dam is not expected but localized damages can be seen. Nonlinear analyses is suggested for the assessment of the possible damage on the system. Similarly, Yıldız and Gurdil [134] indicate that the maximum tensile stresses occur on the heel and the location of the upstream slope change for the Pervari RCC dam using 2D linear elastic time-history analysis with FLAC2D. The effect of foundation properties on dynamic analysis is presented in the following paragraph.

The Nongling RCC dam was assessed in a 2D configuration using time history analysis in ANSYS by Yong and Xuhua [110]. The consideration of the infinite foundation effects with the radiation damping was determined to reduce the dynamic response by 20 to 30 %. In contrast to the use of a finite foundation boundary, the radiation damping of infinite foundation (modeled using springs and dampers) influences the vibration energy reduction of the system. Bakarat, Malkawi and Omar [115] investigated the effect of the foundation properties and variations in the batter slope (i.e. the slope on the bottom of any face of a dam supposed to be different from the major slope at that face) on the seismic performance of the Tannur RCC Dam using SAP90. The assessment of accurate soil mechanical properties was determined to have a great effect on the stresses. This effect was limited to the foundation only, and negligible within the dam body. Increasing the slope of the upstream batter reduced the extent of the tensile stress zone at the foundation, but did not affect the maximum tensile stresses. Similarly, Wieland, Malla and Guimond [121] studied the effect of different foundation elastic moduli on the dynamic response of Nam Theun RCC arch dam.

The softer foundation stiffnesses were determined to result in lower dynamic stresses on dam body but the reduction was not in high levels. On the other hand, varying of the foundation stiffness influenced the crest acceleration and deformation of the dam with an inverse relation. Guangting, Penghui,Yu and Fengqi [122] also suggest that soft foundations with lower stiffness lead to higher deformation capacity for RCC arch dams while the tensile stresses would be distributed through abutments strengthened with concrete sidewalls, aprons and flexible bands in the arch tensile area. Building RCC arch dams on soft foundation was determined to be more desirable such as the Shimenzi RCC arch dam. The fragility analyses of several RCC dam cross sections conducted by Restrepo-Velez and Velez [126] using EAGD-84 support this thesis. Lower dam/foundation moduli ratio (E_c/E_f) value decreases the risk of damage since the flexibility of foundation enables the structure to dissipate energy better with higher deformation capacity. Milder slopes for the downstream side was also determined to reduce the level of damage.

According to USACE-EP-1110-2-12, "Seismic Design Provisions for Roller Compacted Concrete Dams"[19], when the computation accuracy of analysis conducted with 2D and 3D models are compared, as mentioned before, the geometry of the dam and topograghy of the site play an important role in resulting stresses and possible cracks. 2D models do not represent the actual distribution of stresses and locations of cracks on a curved axis due to transferring of stresses into the abutments. The monoliths with irregular transverse cross section across the width also may not be analyzed by 2D methods. Therefore, 3D effects should be taken into account to estimate the real performance of RCC dams constructed on curved, narrow valleys or without transverse joints in long valleys [119][120].

3D linear elastic analyses of RCC dams are scarce. Lei and Zhenzhong [111] analyzed the Madushan RCC Dam using a 3D FEM model by ANSYS.

The maximum tensile stress occurs at the heel of the dam similar to the results from the 3D linear elastic FEM analysis on the Cine Dam by Kartal using ANSYS [114]. For the full reservoir case, the maximum principal stress components increased in the vertical direction with increasing reservoir level. The relative horizontal displacements and principal stresses increased, approaching from the middle to the side blocks of dam body.

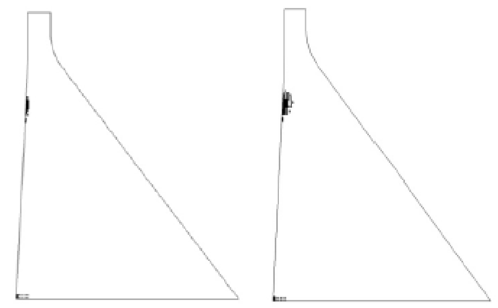
2.1.2.2 Nonlinear Inelastic Analysis

Exceedance of the allowable tensile stresses indicates expected cracking on the dam which can be assessed using nonlinear inelastic analyses (in time domain). Because of the required input to such analyses in terms of the material models, this approach is considerably harder and more time consuming compared to linear elastic analyses. Cracking models are usually preferred to general plasticity models in the modeling of the concrete for dam systems.

Cracking in concrete dams is usually modeled using the “discrete crack” or the “smeared crack” approach. Discrete crack modeling involves prescribing the location of the crack in the analyses. The modeling of the crack propagation in this fashion requires staged analyses and updating of the finite element mesh for the simulation of the crack propagation. The model is not much preferred due to its incremental nature as well as the computational cost in using adaptive meshing strategies. On the other hand, in the smeared crack model, the cracks in the elements are represented by softening of the stress-strain curve and the resulting modified stiffness matrix. The crack propagates using these softened elements in the original mesh, allowing the consideration of many different crack locations simultaneously. Smeared cracking is much less costly, generalizable and easier to apply for dam structures.

As the crack openings are not physically represented by element seperations in the FEM, the failure to incorporate the water penetration to the models was noted [127][128].

The 2D nonlinear inelastic dynamic analysis of the Pine Flat Dam was conducted by Bagheri, Ghaemian and Noorzad [112]. Lean RCC mixes typically have different stress-strain curve from high cementitious RCC material such that after linear elastic behavior up to nonlinear stage, the secondary hardening stage starts up to ultimate resistance instead of softening behavior observed in conventional concrete dams. The second hardening stage in lean RCC dam enabled the redistribution of stresses from high stress regions such as upstream face and heel of the dam to lower regions of stress and therefore peak stresses and cracking reduced (Figure 2-1). For comparison, the results of same model using the smeared crack model is given which also represents the softening behavior of RCC.


(a)

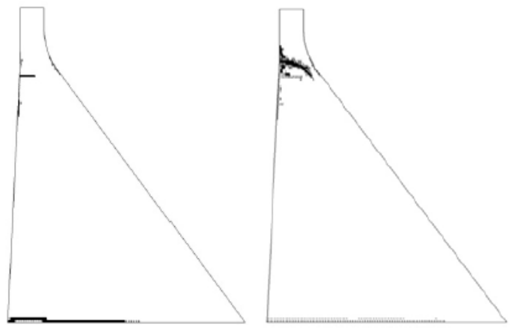

(b)

Figure 2-1 The location of cracking for lean RCC dam (a) hardening model (b) smeared crack approach [112]

2D nonlinear dynamic analysis of the Jahgin RCC Dam was conducted by utilizing smeared crack model in order to investigate the effect of the isotropic and orthotropic behavior of layers on the seismic performance (Mazloumi, Ghaemian and Noorzad [113]). Cracks propagated through the dam body at two regions located around the slope changes of upstream and downstream faces as seen in [116]. Consideration of the orthotropic behavior of the RCC layers led to an extensive zone near the dam’s neck suffering damage, compared to limited damage for the isotropic model (Figure 2-2). Moreover, any discontinuity at upstream and downstream slopes caused extensive cracking due to stress concentrations at these regions.

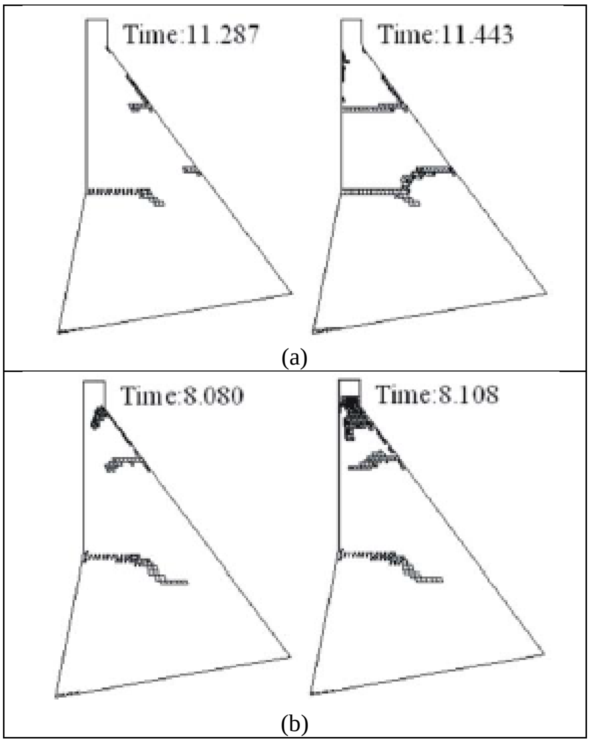


Figure 2-2 The crack profiles of the dam loading (a) isotropic behavior (b) orthotropic behavior for RCC [113]

The Kinta RCC Dam was analyzed with 2D nonlinear dynamic analysis with elasto-plastic deformation model in order to investigate the effects of the sediments on the seismic behavior of the dam. RCC dam-bedding rock foundation was modeled by thin layer interface. There was a redistribution of the stresses at thin layer interface with reduced stresses as a result of energy dissipation through deformation in this region [133].

A similar cracking (at the dam-foundation interface propagating towards downstream) was observed during the 3D nonlinear analysis of the Guandi RCC Dam which does not affect the safety of dam [116]. In Jinanqiao RCC dam, reinforcement was used on both the upstream and downstream sides on abrupt slope changes at the heel and neck as a result of 3D analyses [123][125]. According to Jiang, Du and Hong [132], the use of steel reinforcement decreases the sliding displacement and joint opening of the system.

3D nonlinear analysis for the Cine Dam with the kinematic hardening material model and 2D nonlinear analysis with the discrete crack model for the Pervari Dams in Turkey are presented in (Kartal [114] and Gurdil and Yildiz [134]), respectively.

Shapai RCC arch dam is the first RCC dam that experienced a strong earthquake. It was hit by the Wenchuan earthquake with a magnitude of 8.0. The PGA at the site is predicted to be between 0.25 to 0.50g compared to the design acceleration of 0.1375g. The body of dam was undamaged after earthquake [135]. The nonlinear dynamic FE analysis was conducted by Li, Jiang and Xie [[136] to compare the monitored earthquake response of the dam from the site with the results of analysis. They concluded that the size of the openings along the joints are comparable with the monitored data.

The propagation of cracks on the dams may occur for reasons other than seismic loading. Very high RCC dams was determined to be prone to the so-called hydraulic fracture effect due to the considerably large reservoir head and pressure acting on the dam. For a 285 m high RCC dam, the crack at the heel was determined to increase from 2m to 16m modeling the incremental rise of the reservoir in a staged analysis with discrete crack model. (Jinsheng, Cuiying and Xinyu [124]) Additional measures to prevent cracking at the heel may be required for such dams.

2.2 Thermal Analysis

2.2.1 General

Thermal analysis plays an important role in the structural design. The heat generation resulting from the cementitious reaction causes temperature rise in the

RCC dam body during and after construction. This temperature reaches a peak value in several weeks after placement, followed by a slow reduction to some degree. In some cases, this process takes months and even years to finish completely. During this process, thermal stresses are developed due to restraints and temperature differentials within the dam body. These stresses can be significant and may lead to thermally induced cracks which may threaten the durability of the structure [70].

The cracks observed on mass concrete structures like RCC dams are usually categorized as “surface gradient cracking” and “mass gradient cracking”. Surface gradient cracks are induced as a result of the faster cooling of the dam surface with respect to dam body. They are generally minor cracks occurring on the dam surface and do not jeopardize the safety of dam. However, mass gradient cracks develop from the vertical temperature differences within the dam body. Dangerous horizontal cracks may be induced especially if the dam is restrained by rigid boundaries such as rock foundations. This type of crack should be prevented, otherwise the tensile stresses which is higher than lift joint tensile strength may deteriorate the stability and durability of dam [71]

The exposed surface area of RCC dams are larger than that in CMC since it is placed as thin layers while CMC is poured with a mass concrete lifts. Heat gain and loss is more critical for RCC. Additionally, the placement time interval and speed can be more important for RCC because of the solar heat absorption. Thus, thermal considerations need significant attention while designing a RCC dam. Thermal analyses provide guidelines for optimizing the mixture content, implementing the necessary construction requirements such as RCC placement rate and temperature, and the consideration of site conditions [2].

The cementitious content of a mix directly affects the thermal behavior of RCC dams. Mix with high flyash / cementitious content ratio leads lower heat of hydration in early ages which is critical to prevent thermal stresses. Besides, mixes with high cementitious content cause temperature increase in dam body in the long term which results in mass gradient cracks.

2.2.2 Analysis Methods

Analyses to investigate the thermal performance of RCC dams were categorized into three main formulations in the USACE (ETL 1110-2-542, “Thermal Studies of Mass Concrete Structures”). Each one of these analyses is used frequently based on the complexity, size, type and the function of the structure. Small RCC weirs can be analyzed with Level 1 thermal analysis while the ones with massive sizes require more detailed and complex analyses like the ones prescribed in Level 2 and Level 3. The use of Level 2 and Level 3 thermal analyses were deemed to be crucial for high RCC gravity and arch dams [72].

2.2.2.1 Level 1 Thermal Analysis

This method (also known as Simplified Thermal Analysis) is described in [72] as the simplest tool for calculating the vertical contraction joint spacing of mass concrete structures. The required parameters are well-known and easy to obtain. There is no laboratory or site testing required for calculations. The average monthly temperature of site, concrete placement temperature (which can be taken as the average monthly temperature of site or making assumption based on the placement season), thermal expansion coefficient, adiabatic temperature rise, elasticity modulus and the tensile strain capacity of concrete are the required parameters.

For the temperature analysis, the peak concrete temperature and the final stable concrete temperature are calculated. The difference is then used as the parameter for cracking analysis. The mass gradient cracking analysis is done calculating the mass gradient strains; these strains are then compared to the tensile strain capacity of the concrete in order to evaluate the possibility of cracking. The mass gradient strains are calculated with the following formula:

$$Total\ Strain = (C_{th})(dT)(K_R)(K_f) \tag{2.1}$$

where,

C_{th} = coefficient of thermal expansion

dT = temperature differential

K_R = structure restraint factor

K_f = foundation restraint factor

Finally, the cracking strain is determined by taking the difference of the total strain expected and the tensile strain capacity of concrete. The total crack width along the length of the dam body is obtained by multiplying the cracking strain with the length of the dam body. An admissible crack width is assumed, and the number of cracks forming on the dam body is determined by dividing the total width of cracking to the admissible crack width (can be taken 0.002 mm for stiff foundations and up to 5 mm for flexible or yielding foundations). Lastly, the estimated crack spacing is computed by dividing the width of dam to the number of cracks.

Level 1 Thermal Analysis is generally used for smaller mass concrete structures and weirs. It was used in temperature analysis of the Cindere Dam, as the dam was a hard fill type with low cementitious content in which low heat of hydration generation was expected [56]. Similarly, in the design of the RCC portion of the Saluda Dam remediation project, this method was applied [73].

2.2.2.2 Level 2 Thermal Analysis

This analysis method includes a more comprehensive study in many ways compared to the Level 1 analysis. Instead of computing a single generalized thermal mass strain and crack spacing as in Level 1, nonuniform thermal gradients on both the mass and surface of the dam body are calculated in any location of the dam separately by considering the temperature difference between horizontal or vertical elevations of the dam section. In this process, many additional variables are used in order to increase the accuracy of the final thermal strain and stresses found from the thermal loads.

Level 2 is generally used for determining the thermal stresses and possible cracks that a mass concrete structure may develop after the construction and cooling processes. The heat of hydration of RCC mix during and after construction leads temperature rise inside dam body with the effect of fast placement. During the dissipation of this heat, significant temperature differences are observed in different parts of RCC dams which causes thermal stresses in the structure. If these stresses possess a risk for the durability, loss of function or the stability of dam, then Level 2 analysis is necessary even for the feasibility study of high RCC gravity and arch dams or in the detailed study of medium to high RCC gravity and low-head RCC arch dams.

The finite element (FE) method is widely used in computer aided thermal analyses. Level 2 analysis can be conducted either using 1D strip FE and/or 2D&3D FE analyses.

These models are both capable of calculating the mass and surface gradients within a system, however 2D&3D models are more preferable because they lead to the determination of the thermal gradient on a "section" of a body rather than "strip". This enables the user to have a better insight about thermal gradients on any point on the body. In more detail, 1D strip models lack the capability of computing the horizontal heat flux in a mass gradient analysis; so that after the construction is finished and the core concrete starts to cool down, 1D model underestimates the temperature differences between vertical meshes due to the its failure to consider the horizontal heat flux through the surface of the dam.

Cervera, Oliver and Prato [74] faced this problem while evaluating the Urugua-i RCC Dam for thermal strains. They concluded that 1D model can be used for a time period between the start and the end of the construction, but for analyses focused on the long term temperature effects, the 2D&3D analyses represent the phenomenon more accurately. On the other hand, there are some studies conducted in order to enhance the long term temperature gradient prediction of 1D strip models. Cervera and Goltz [75] used a modified FE code to predict the long term behavior of temperature in the core of Rialb RCC Dam. The results are compared with the data obtained from the installed thermometers during construction showing good correlation. With the advance of computational power, the use and validity of 1D strip models are not widespread. This method is usually utilized for preliminary thermal analysis of RCC dams. A typical 1D strip model for thermal analysis is presented in Figure 2-3.

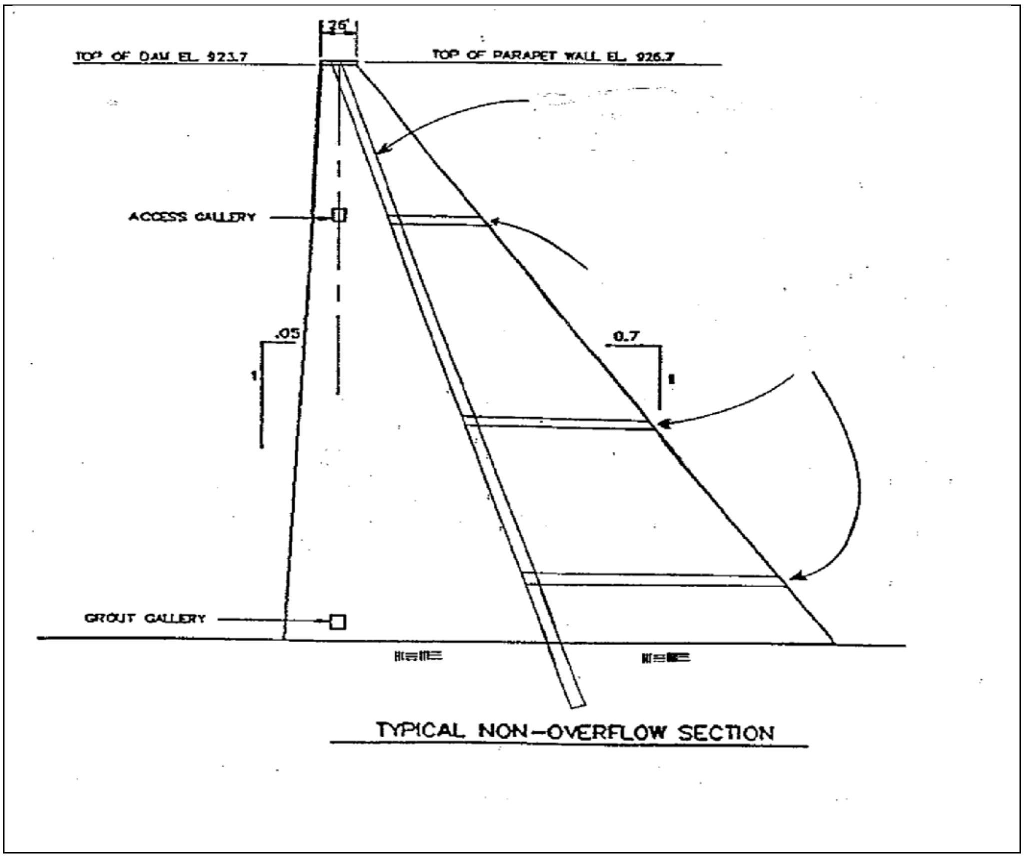


Figure 2-3 Mass Gradient and Surface Gradient Strip Models for 1D FE Model

The 2D&3D method results can give more accurate information about the thermal design of RCC dams such as the construction schedule, placing temperatures and the contraction joint spacing especially for those systems having massive sizes and high elevations. The methodology of thermal analyses using 2D&3D models is almost the same with simplified method and 1D Strip models. However, more input parameters are needed for this detailed procedure. The parameters that must be known before starting the analysis are listed as below:

1) Site parameters: average monthly temperatures, wind velocity, solar radiation etc.

2) Material parameters: modulus of elasticity of the RCC mix and the foundation, thermal conductivity, coefficient of thermal expansion, adiabatic temperature rise of the mixture(s), specific heat etc.
3) Construction parameters: concrete placement temperature, foundation rock temperature, thickness and initial temperature of lifts, time interval between consecutive lifts, construction start date, rate of placement etc.

The procedure for Level 2 analysis is summarized below:

1) Determine the site, material and construction parameters,
2) Prepare temperature model. Step by step integration method or FE models may be used,
3) Compute temperature histories. Tabulate temperature data as temperature-time histories and temperature distribution to obtain visual results,
4) Conduct surface and mass gradient crack analysis with using temperature distribution obtained before.
5) Use Equation (2.1) to determine thermally induced strains, convert it to stress and compare with the tensile strength capacity.

The expected outputs from the 2D&3D thermal analysis of RCC dams are as follows [82]:

1) The determination of distribution of temperature field and its evolution with time
2) The determination of stress field during and after construction
3) The determination of appropriate joint spacing to prevent cracking

The computation accuracy of 2D&3D thermal analysis is mainly dependent on the assumed or computed input parameters. Platanovryssi Dam [88] was modeled with both 2D&3D FE analyses. It was observed that the thermal properties of the mixture affects the thermal gradients significantly so that hydration heat and adiabatic temperature rise test should be done carefully before the construction starts. Moreover, tensile strain capacity of RCC should be tested to evaluate cracking properly [72]. Thermal behavior of RCC dams is very complex, which is mostly due to the large uncertainties in the used parameters rather than the methods and computation procedures [76].Urugua-i RCC Dam [74][81] was modeled with a 2D FE mesh. Real construction process of the dam was simulated in the model and the temperature field inside the dam body at any point was successfully calculated. The bottom part of the dam was observed to be exposed to the highest tensile stresses due to the high temperature field and the restraint of the foundation. Badovli Dam, built in a cold region was modeled by ANSYS using a 2D model, and the surface and mass gradient analyses were conducted [77], leading to similar results. During the thermal simulation of Kinta Dam, initial tensile stress increase due to heat of hydration of cement within the first days was observed [79][80]. Investigating the effect of temperature change on the elastic and creep parameters, it was determined that significant increase in the modulus of elasticity during the initial hydration process led to high tensile stresses at the beginning of construction. Again, it was underlined that the bottom part of the dam near the foundation reaches the highest temperatures in the dam body due to massive volume and this zone possessed the highest risk for the cracking due to high tensile stresses especially at the heel. In conclusion, for mass gradient analysis, the zones near the foundation appear to be more critical in nature, reaching maximum tensile strains in dam section due to strong restraint of the foundation rock.

For surface gradient analysis, very low air temperatures increase the risk of surface cracks which can lead to increased seepage through the dam body.

In addition, in the 3D thermal analysis of Jiangya RCC Dam, it was concluded that very hot air in summer time also triggers the surface gradient cracks in RCC dams [85]. Surface cracks are very dependent on the ambient temperature: increase or decrease of the air temperature leads to compressive or tensile stresses, respectively. The temperature difference between inner and outer zones of the dam causes surface cracks [86] [87]. As a precaution, the cooling of the aggregates before placement was suggested [77].

Chao, Anzhi, Yong and Qingwen [78] analyzed the Longtan RCC Dam with ANSYS. The temperature of the dam increased rapidly in the first days due to heat of hydration and reached a maximum value. During this period the surface attained high tensile stresses due to temperature difference with the core. After the cooling stage began, the surface cooled down more rapidly than the core that led the surface to attain compressive stresses while the core was exposed to tensile stresses as in [83][84]. In other words, with the aging of the concrete, the tensile stresses transferred from the surface to the core of the dam. Hydrostatic pressure on the upstream of the dam was determined to reduce the tensile stresses induced by the temperature field. Finally, if the computation accuracy of the 2D and 3D FEM analyses are compared relative to real measured data from dam sites, both of them are seen as adequate and yield results in good agreement with the actual thermal measurements. 2D analysis takes the advantage of saving time during the computation [84][88][82]. A technique called “relocating mesh method” was also used by various authors [86][91][92][93][94] reducing the computation time significantly. In this method, the mesh layers of thin lifts are merged into the larger lift and the number of nodes and elements are decreased significantly.

The discontinuity of the temperature field at the lift joints were considered by Chen, Su and Shahrour [90] introducing the so-called “composite element method (CEM)” principally based on FEM.

The temperature difference across the lift joint between the new and old concrete can be higher than $10^{o}C$ in daytime. The temperature discontinuity between old and new lifts of RCC can be computed with this method helping to predict early-age concrete cracks better.

2.2.2.3 Level 3 Thermal Analysis

This level can be regarded as the most comprehensive approach for thermal analysis of RCC dams and named as “Nonlinear Incremental Structural Analysis”. Level 3 (NISA) is used generally for very critical structures subjected to extreme loads where cracking threats the integrity of structure significantly. Very high gravity and arch dams can be put into this category [72]. Elimination of cracking is not the objective of this method. On the contrary, NISA calculates both mechanical and thermal loading effects simultaneously, taking the temperature vs. stress-strain relationship and material nonlinearity into account to predict maximum possible crack lengths that a structure may be exposed. Over-design of critical structures can be prevented in this fashion. The detailed procedure and an example of this level of calculations are given in [95][96].

2.2.3 Temperature and Crack Control Measures

The control of temperature increase and variation in a RCC dam is essential to prevent undesirable high stresses and possible cracks. The maximum temperature of concrete in large RCC dams can rise to very high values especially if construction is commenced in hot seasons. In order to control the temperature fields and crack propagation within the RCC dam during and after construction, some measures should be kept in mind.

The lift thickness, layer placement break, cementitious content amount, placement temperature influence the maximum temperature that the RCC can reach. Thinner lifts have better heat conductivity than thicker ones so that the heat dissipation occurs more easily. Moreover, the breaks between pouring of adjacent lifts or sections enable the bottom lift to cool down before the next lift is poured. The placement temperature of concrete also influence the temperature rise significantly. The temperature of pouring concrete should be kept low as possible as to reduce final temperature. Furthermore, the RCC mixtures having lower cementitious content tend to release lower heat of hydration so that they reduce the rate the temperature rise [2][71][86][88][89][97].

The starting season of placement is the key factor for controlling the final temperature of RCC. In order to prevent high tensile stresses and mass gradient cracks at the restrained zone near the foundation, the placement of RCC should not be started in hot seasons [98] [100] [89]. The placement of RCC was prescribed to start at April for the Aladerecam RCC Dam using the 2D FEM models [37] to compare placement start dates. In addition, aggregate pre-cooling, use of ice or chilly water in the mixture, low temperature placement and surface insulation are the other important precautions to reduce heat evolution in RCC. Taishir Dam, built under high seasonal temperature differences varying between 50^{o}C and 40^{o}C, was insulated using impervious upstream PVC geomembrane facing in order to protect concrete from extremely low temperatures [109]. Pipe cooling can also be used for large dams constructed in hot seasons but it is not recommended practically since pipes can be damaged during the compaction of RCC layers [99] [100] [101] [102].

Finally, thermocouples, vibrating wires and thermistors permit the spot measurement for controlling the temperature rise and variation in RCC dams, but distributed fiber optic cables were used more recently to monitor the temperature changes in RCC dams.

The biggest advantage of these are the collection of the data from a line of fiber optic cable, not a spot, which enables the user to observe temperature variations within a dam more conveniently. Stress meters, distributed temperature and strain sensing are the other instrumentations used for temperature monitoring [103][104].

2.2.4 Thermal Cracking in RCC Dams

Cracking was observed at various RCC dams due to thermal reasons. For example, the Upper Stillwater Dam, one of the earliest RCC dams with a significant amount of monitoring, experienced several thermally induced vertical cracks due to very high cementitious content which leads to increased stiffness, modulus of elasticity and less creep relaxation in the long term. Seven of these cracks were sealed with poly-urethane grout, while drains were installed in several others to divert the seeping water and relieve the water pressure. Three of the widest cracks were treated with corrugated stainless steel internal membrane. The structure’s durability was not affected [24],[41][131]. Similarly, the Platanovryssi Dam was exposed to long term thermally induced cracks. A geomembrane system was assembled to repair the cracks underwater [24][137][138].

At Salto Caxias Dam [129], RCC placement in summer time with high placement temperature caused thermal cracks at the middle blocks of the dam. The cracks near the upstream face were treated with fitting a seal and expansion joint. For the cracks at the downstream face near foundation, vertical holes were drilled 1.5m near the face and poly-urethane was injected. Additionally, cracks near the upper gallery were treated in same way with two holes drilled from top of the dam, to a depth of 28m. Crack treatments reduced but did not completely stop the seepage through the dam body and the seepage inspections are continued.

The safety of the dam was not affected. The Puding RCC arch dam [130] suffered nine cracks due to placement in high temperature seasons and the strong restraint provided by the rock foundation at the bottom and valley sides. The two of cracks were treated with chemical grouting where leakage was inspected. At Galesville, Elk Creek, Hudson River, Deep Creek, New Victoria and Pangue RCC dams, thermally induced cracks were observed after completion of constructions due to same reasons as above. The locations of cracks tended to be at structural irregularity locations where stress concentrations occurred. The transverse joints should be placed at locations such as the gallery entrances, near ends of spillway notch, near abutments where there is closer restraint and a reduction in section sizing [131].

CHAPTER 3

MIX, PROPORTIONING AND MATERIAL PROPERTIES

3.1 Mixture Content

3.1.1 Cement

The cementitious material requirement for RCC are not different from used in CMC. The Portland cement and a suitable pozzolan is used to constitute cementitious paste for RCC. However, since no cooling is used in RCC construction, heat generation should be controlled carefully. For this purpose, the Portland cement types which have low heat of hydration are preferred for thermal consideration. According to ASTM standards, they are Type II Portland cement (moderate heat cement), Type IP (portland-pozzolan cement), Type IS (portland blastfurnace slag cement) and Type IV (low-heat) cement. Type IV Portland cement is not generally used in RCC dam construction because of its rare production in USA. In addition to this, Type III Portland cement is not usually selected since is shortens the time available for compaction and increases heat generation at early ages [6].

Before selecting the type of cement to be used in RCC, the engineer should determine the early and long-term strength requirements of design mixture. The cement types with low heat generation tends to produce design mixtures with slow rate of strength development when compared to Type I Portland cement but, in the long term these types of cement produce higher ultimate strength values when compared to Type I. Besides this, the temperature rise within the dam body of RCC dams having massive concrete mass is relatively high than in small-size RCC dams so that using the cement with low heat of hydration is especially important for massive structures. Finally, the last but not least, the availability of any cement type near an RCC dam site is very important criteria in decision making [1]. The mixture content of some RCC dams from literature is given in Appendix A Table A.2.

3.1.2 Pozzolan

3.1.2.1 General

Pozzolan is used in high contents in the application of RCC. " Class C, Class F flyash and Class N natural pozzolans have been used in various RCC projects. Among these, Class F and Class N type of fly ash, blast furnace slag and natural pozzolans are more commonly used because they generate less heat of hydration and have greater sulfate resistance. The use of pozzolan is directly related to design mixture requirement as well as thermal considerations, cost and the availability of material for each project. Pozzolan is used in RCC mixtures for the following purposes: [6]

1) To reduce heat generation: Partial replacement for cement [13],[54]
2) To reduce cost: Partial replacement for cement to reduce cost
3) To improve mixture workability: Additive to provide supplemental fines for mixture workability
4) To improve impermeability and minimize the alkali-aggregate reaction.

3.1.2.2 Replacement Ratio

The rate of replacement may change from 0 to 80 %, by mass. Design mixes with high content of cementitious material usually use high percentage of pozzolan to reduce adiabatic temperature rise. In addition, for design mixes with high content of Portland cement, using pozzolan improves long-term strength of the mix since there is sufficient amount of calcium hydroxide released from the Portland cement for a pozzolanic reaction and vice versa [4].

However, according to Hamzah and Al-Shadeedi [7], partial cement replacement by pozzolans causes reduction in compressive strength at early ages. Good results can be obtained after 90 days and more.

The price ratio of cement to pozzolan is a key factor in order to benefit from replacing cement with pozzolan. Some factors such as availability of pozzolan near project site, quality and quantity of pozzolan affect the price ratio of cement to pozzolan. Furthermore, the cohesion of the mixture increases due to increase in the fines content which reduces segregation and it occupy void space leading increased workability and impermeability [5].

The permeability of RCC is improved in the presence of admixtures due to filler and pozzolanic action.

The values obtained with powdered aggregate, metakaolin, silica fume and rice-husk ash are satisfactory for RCC of about 10^{-10} m/s. With blast furnace slag, fly ash and natural pozzolan concretes, the permeability is much lower around 10^{-11} m/s. The fly ash and blast furnace slag have especially superior results in terms of a denser microstructure, a good paste/aggregate adherence, low permeability and absorption and higher compressive strengths.

Finally, it is very important that each design mixture of each RCC project requires different amount and percentages of pozzolan to meet conditions. According to Andriolo [6], unreasonable use of pozzolans is not welcome because the adequate content of pozzolan is determined by its pozzolanic activity with the cement.

3.1.2.3 Use of Fly Ash and Limestone Powder

The use of fly ash is particularly effective in RCC mixes which provide additional fines for easy compaction. Although fly ash reduces early age strength of RCC mixes because of the slowing down concrete set, it provides long-term improvements in strength due to pozzolanic reaction which leads to consumption of free limes into stable hydrates by pozzolanic reaction. According to Park, Yoon, Kim and Won [9], the compressive, tensile and shear strengths of the RCC mixture without fly ash were greater than those of the RCC mixtures with fly ash at early age, but the mixtures with fly ash were more effective than those without fly ash in terms of long-term strength. Fly ash also minimizes the effect of alkali-aggregate reaction. A similar study was carried out by Atis [10]. He investigated the relationship between the mechanical properties of the RCC and the replacement ratio of cement to fly ash with focus on strength of very high volume fly ash mixtures with very low and optimal W/C (water/(cement+pozzolan)) ratio.

This study underlined that very high fly ash replacement ratios may not be feasible and technically appropriate for using in mass RCC applications. On the other hand, the Chinese RCC experience show that when the quantity of high quality fly ash is abundant near the dam site, the design can be made for high volume of high quality fly ash content.

Due to increase in the popularity of the high quality fly ash in concrete industry, Chen, Ji, Jiang, Pan and Jiang [11] investigated the effects of limestone powder as a pozzolan with replacement to fly ash content. They concluded that the compressive strength decreased slightly with the fly ash replacement by limestone which consists more than 20% stone powder content. Stone powder has no significant pozzolanic activity and had no contribution to the strength development in the later ages. The study by Kaitao and Yun [12] supports the results of the above study. The influence of limestone powder replacing the fly ash to use as admixture affected workability, permeability and freeze-thaw performance well, and setting time of concrete shortened, the adiabatic temperature rise value lowered, but mechanical properties of RCC reduced with increasing limestone powder content.

3.1.3 Aggregate

3.1.3.1 General

The aggregate is a very critical part of the RCC mixture content. Approximately 75 to 80 % of the mixture volume is possessed by the aggregate. The selection of aggregate, control of the aggregate properties and grading are important factors affecting the quality and uniformity of RCC mixture. Traditional aggregates used in CVC can be used in RCC.

The aggregates meeting the “ASTM C 33 Standard Specification of Concrete Aggregates” are generally used for RCC production. In addition, marginal aggregates that do not meet traditional standards have also been used in many RCC dam construction successfully [1].

3.1.3.2 Effect of Quality

Economy, availability and distance to site are the important factors that should be checked before selecting the aggregate. Aggregate selection affects the mechanical properties significantly, the design considerations should be revised if any other type of aggregate is used in construction instead of pre-selected one [4].

The use of low quality aggregate can be tolerated in mass concrete applications, such as in the Concepcion Dam [2], Middlefork Dam, Wyaralong Dam and Koudiat Acerdoune Dam. A redesign of the dam section such as for the Middle Fork Dam can be done in accordance with the chosen aggregate material [2]. In combination with high creep, low modulus of elasticity matched with the foundation characteristics, the poor quality sandstone at the Wyaralong Dam site [14] allowed the reduction of thermal stresses providing the oppurtunity for placing with no cooling. With the crucial washing and screening process, minimum period of stockpiling and careful transportation to minimise further breakage, weak alluvial aggregates were used at the Koudiat Acerdoune Dam achieving the desired design strength values. Core strengths were obtained to be 35 % lower than the sample laboratory strengths[15].

3.1.3.3 Effect of Shape

For RCC, flaky and elongated aggregates affect the mixture uniformity, segregation and strength much less than the one for CVC as the vibratory compaction equipment gives more energy than traditional methods and the higher mortar content in RCC separates coarse aggregate particles [6], [57]. The flaky and elongated aggregates may decrease the density of RCC mixture and increase cement and water demand.

Field test shows that flat and elongated particles cause no serious problem for RCC application [6] [4]. However, the real dam applications can experience different results than the usual point of view. For example, in the Koudiat Acerdoune RCC dam, the rounded shape of the alluvial aggregate made lift surfaces preparation difficult and time consuming. The contractor implemented Slope Layer Method to reduce effects of these problems. Slope Layer Method is a method which enables each layer of RCC to be placed within the initial set time of the previous layer. This improves horizontal lift joint strength and impermeability [15]. Furthermore, the use of rounded and flaky aggregates in Yeywa Dam resulted in high water demand and low strength than expected [53].

3.1.3.4 Effect of Aggregate Crushing

The use of crushed and uncrushed aggregates directly affects the mechanical properties of RCC mixtures. Hamzah and Al-Shadeedi [7] showed that using crushed aggregate increases the interlocking between particles of aggregate and gives better mechanical properties than with uncrushed aggregate. On the other hand, uncrushed aggregate increases the void space, thus decreases density and needs more W/C ratio (Figure 3-1).

These conclusions are supported by the experience in Yeywa Dam: the use of crushed instead of rounded and flaky aggregates improved the compressive strength significantly [53].

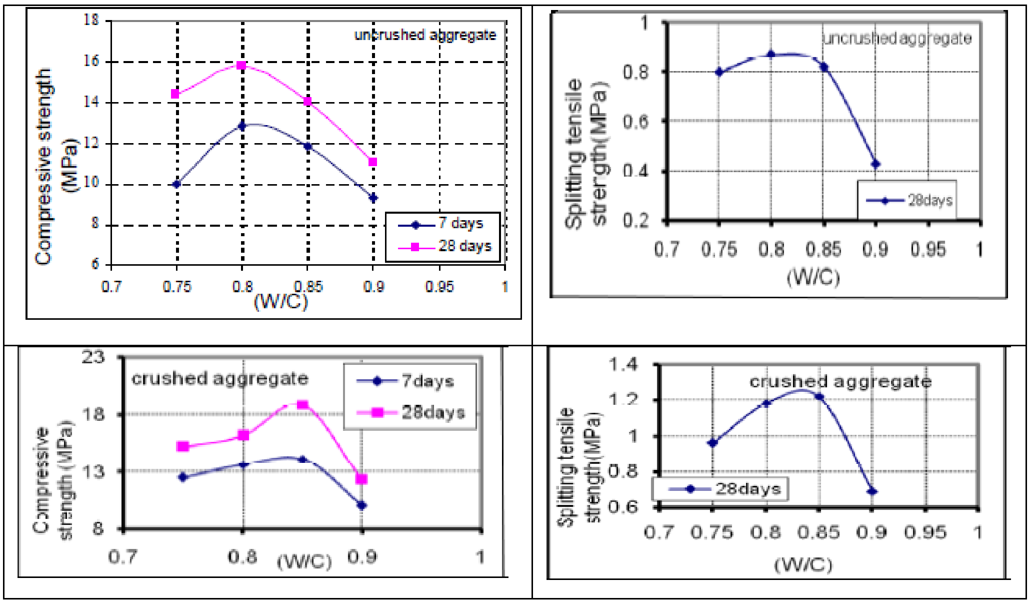


Figure 3-1 Variation in compressive and tensile strength with W/C ratio and aggregate crushing[7]

3.1.3.5 Effect of Size

The main purpose in mixture proportioning is to incorporate the maximum amount of aggregate and minimum amount of water into the mixture, thus reducing the cementitious material quantity and reducing the potential volume change of the concrete. By using a well graded aggregate with the largest maximum size, this purpose is accomplished. The mixture with both adequate paste and minimum cementitious content was formed. On the other hand, potential segragation and difficulty in compaction of the concrete have to be considered while selecting maximum size of aggregate to be used in mixture.

In the past, 75 mm (3 in.) NMSA was used in the US but nowadays 50 mm (2 in.) is more widely used which is less prone to segregation, increasing lift-joint quality and reducing compaction equipment maintenance.

3.1.3.6 Use of Fine Particles

Fine aggregates whose diameter is less than #200-0.075 mm are crucial for paste requirement and compactability of RCC. spaces. Fine particles increases water but decreases cementitious material demand, increases compactibility with filling voids and thus decreases the passing number of vibratory rollers to fully compact the RCC lifts [44][1]. The maximum density of the RCC mixtures is generally optimised by proportion of fine aggregates in the mixture. Most RCC mixtures uses 3 to 8 % of fine particles in the total aggregate volume. This percentage can be higher if aggregates with high NMSA are used with large volume in the mixture [4]. At Olivenhain Dam, 32% of fine aggregate was used to obtain maximum density [51]. Fine aggregate percentages of 34% and 35% were used in Upper Stillwater and Beni Haroun Dam [55]. In Hiyoshi and Tomisato Dams, fine particles are used in order to improve consistency of the mix and workability during compaction [38].

Plastic fines are not acceptable as the workability of the mixture is reduced considerably. The weakness of marl and shale particles included in the aggregates with plastic and clayey fines increased the Vebe time rapidly with time and RCC progressively lost its workability [15]. A set retarder was introduced into the mix (0.5 to 0.8% of cement weight) to compensate for this effect.

3.1.3.7 Effect of Gradation

Generally, three or four aggregate sizes are used in RCC dams [4][6]. At Olivenhain,Upper Stillwater,Cindere and Beni Haroun Dam, three sizes of aggregates(two coarse and one fine) were used to obtain required aggregate gradation curve [51][55][56]. Moreover, the aggregate variability in each stockpile should be minimum as possible as in order to avoid segregation in stockpile. The construction of stockpile and delivery of aggregates from stockpile to construction area are very important factors affecting the gradation and leading segregation. In order to avoid possible segregation, slightly finer aggregate than actually needed can be stockpiled [30].

Figure 3-3 shows some sample aggregate gradations for RCC Dams. They all exhibit good workability except Willow Creek Dam [2].

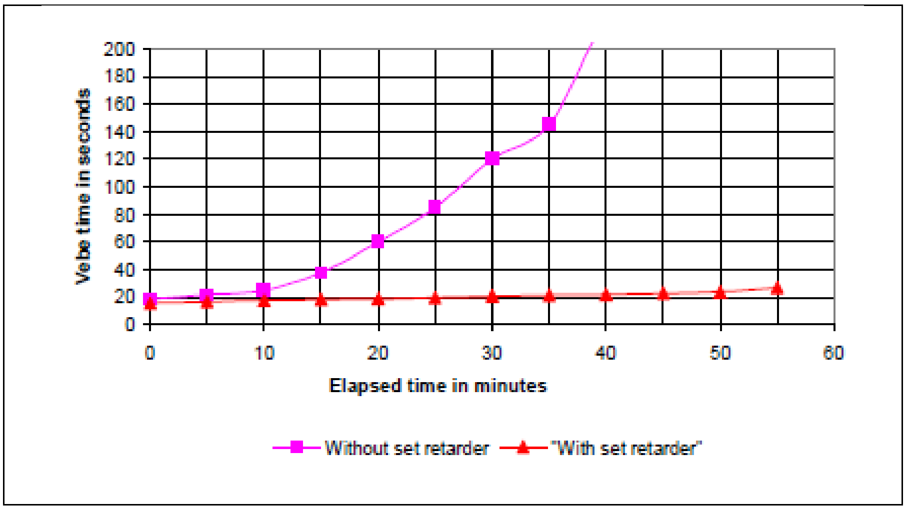


Figure 3-2 Vebe time versus time [15]

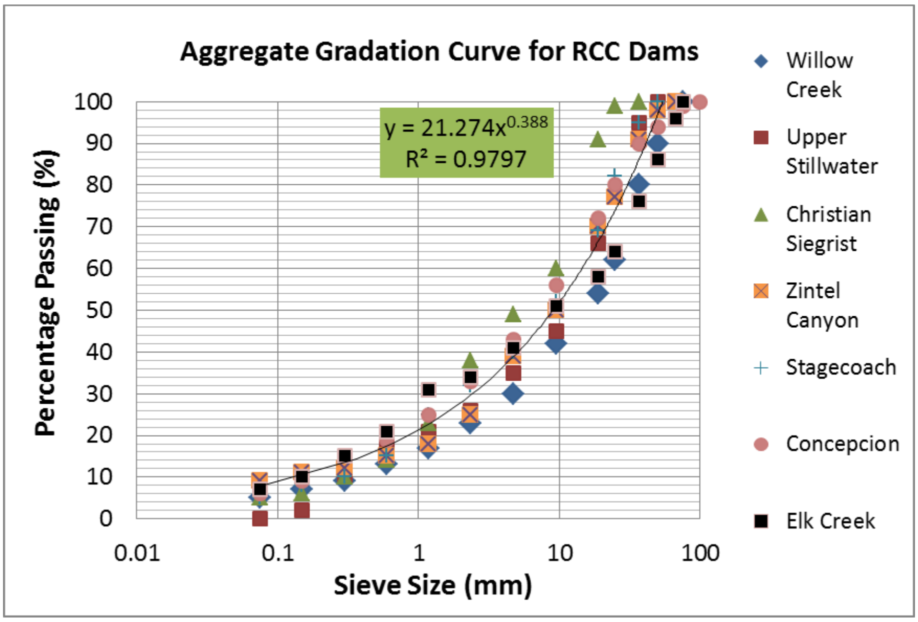


Figure 3-3 Aggregate gradation curve for some RCC dams [2]

3.2 Mixture Proportioning and Design

3.2.1 General

The primary considerations for mixture proportioning are durability, strength, workability and consistency as with CVC construction [4]. In light of the data collected from the RCC dams around the world, the cementitious material content (cement+pozzolan) for RCC dams varies over a broad range from 59 kg/m^3 to 380 kg/m^3. RCC projects have used cement between 30 and 300 kg/m^3, pozzolan from zero to 230 kg/m^3 and produced an average compressive strength between 19.63 and 25.38 MPa at an age of 90 days to 1 year.

While evaluating the content ratio of materials to be used in the design mixture, the largest NMSA, minimum amount of cementitious material, pozzolans and cooling proedures for the materials are taken into consideration.

Site-specific requirements play an important role such as location and size of the dam, performance of dam foundation, climate, availability and quality of materials. According to Ancieta and Ongalla [22], Grand Poubara RCC Dam, located in Gabon, was designed based on the vertical tensile strength among each layer required due to the high seismic activity in the region. Regardless of the material specifications chosen, the testing and evaluation of laboratory trial mix batches are crucial to verify the fresh and hardened properties of the concrete [1].

The important elements in the proportioning of RCC for dams is the amount of aggregates and paste. The paste consists of water, cement, pozzolan and fines in other words, all the ingredients of RCC mixture except coarse and fine aggregates. It should fill aggregate voids and produce compactable, dense concrete mixture. The paste consistency is very important for strength and watertightness at horizontal lift joints. Low cementitious contents generally require more fines to fill aggregate voids for consistent mixture. The gradation of aggregates and batching is also essential to obtain a uniform and compactable mixture having almost the same mechanical properties in every section of the concrete mass.

3.2.2 Mixture Consistency

RCC mixtures should be dry enough to fully support vibratory roller and not to cause water waving under compacter due to excess water more than needed for filling aggregate voids [2]. The consistency of RCC mix is measured as the time required or a given concrete to be consolidated by external vibration in a cylindrical mold. This time is so called “Vebe time”. Typically, dry consistency mixtures are at or near optimum moisture. They generally have modified Vebe times in excess of 30 sec when that test is used for workability.

These mixtures are affected very little from deformation under truck and tire traffic after compaction. On the other hand, wet consisteny mixtures have modified Vebe times of about 10 to 15 sec and they are much wetter than optimum moisture content. They have insufficient strength between initial and final set to support truck loads. The problem can be apparent at times due to cracking at the lift surface next to tire ruts as shown in Figure 3-4. Rutting of the lift surface at Elk Creek and Upper Stillwater dams was observed to be as much as 50 to 76 mm deep. The consistency of mixture indicates the appearance, not the actual water content being low or high [2]. Similarly, the paste tend to go above the lift surface due to wet consistency and presented deep roller marks and ruts from tires in Saluda Dam [30].

Figure 3-4 Surface damage caused by truck tires on wet-mix RCC [2]

3.2.3 W/C Ratio

W/C (water / (cement+pozzolan)) ratio plays an important role in mixture proportioning. The optimum moisture content is governed by the aggregates so that it is not rational to change aggregates ratio when adjusting the optimum W/C ratio. It can only be accomplished by increasing or decreasing the cementitious material content. Attempts to change the W/C ratio by changing the water content have only minor effects on the W/C ratio. On the contrary, it detoriorates the mixture consistency and cause deviations from optimum moisture content and compactability. The use of very low W/C ratio in RCC as in the CVC only causes to very high cementitious content which leads to higher costs and increased thermal stresses. For obtaining low cementitious mixture, W/C ratio must be high and on the order of 1.0 to 2.0. This is the major difference of RCC from CVC which has W/C values of on the order of 0.4 to 0.6. High W/C ratio does not imply low quality concrete for RCC [2]. The RCC compressive strength as a function of W/C ratio is plotted in Figure 3-5 with the collected data from sites of various RCC dams around the world.

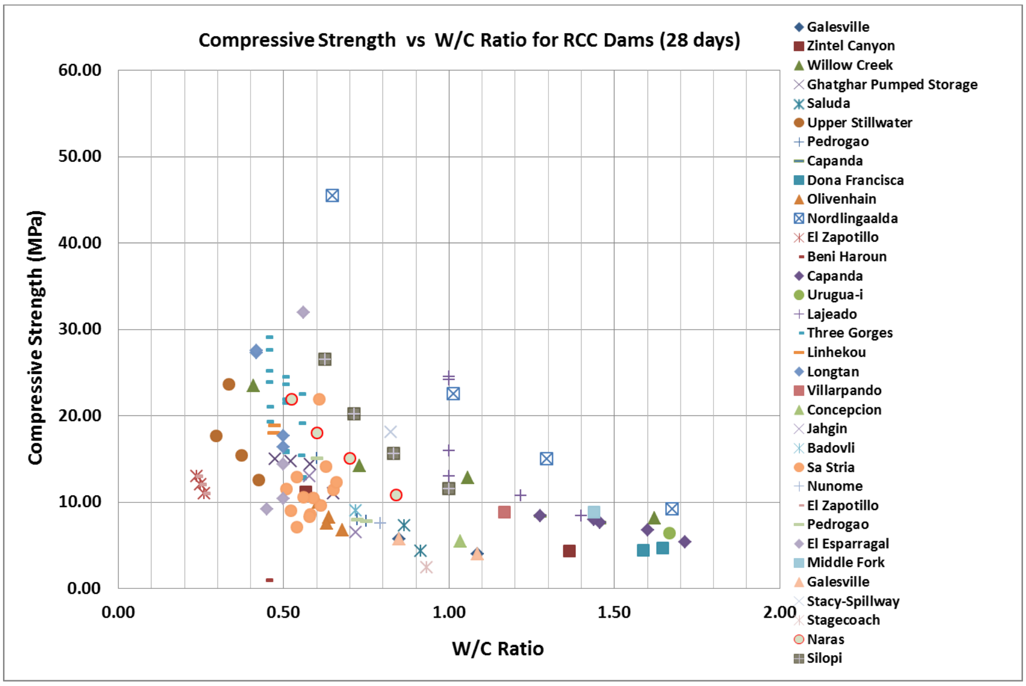


Figure 3-5 Compressive strength versus w/c ratio for RCC Dams

3.2.4 Mixture Proportioning Methods

The mixture proportioning methods generally uses two major principles namely, water / cementitious material approach with the mixture determined by solid volume and cemented-aggregate approach with the mixture determined by either solid volume or moisture-density relationship. RCC mixture proportions are determined by mass of each ingredient contained in a compacted unit volume of the mixture based on saturated surface dry (SSD) aggregate condition. The reason for this is that most RCC mixing plants require mixture ingredients be so identified for input to the plant control system.

The US Army Corps of Engineers use W/C ratio and strength relationship to obtain mass quantities of cement, pozzolan and water for unit volume of mixture as given in Figure 3-6. The approximate W/C ratio can be determined by NMSA and desired modified Vebe time. Fine aggregate and fine content is based on percentage of total aggregates and NMSA used. After the mass and volume of each ingredients are calculated, a comparison of the mortar content to recommended values can be made to check the proportions [3].

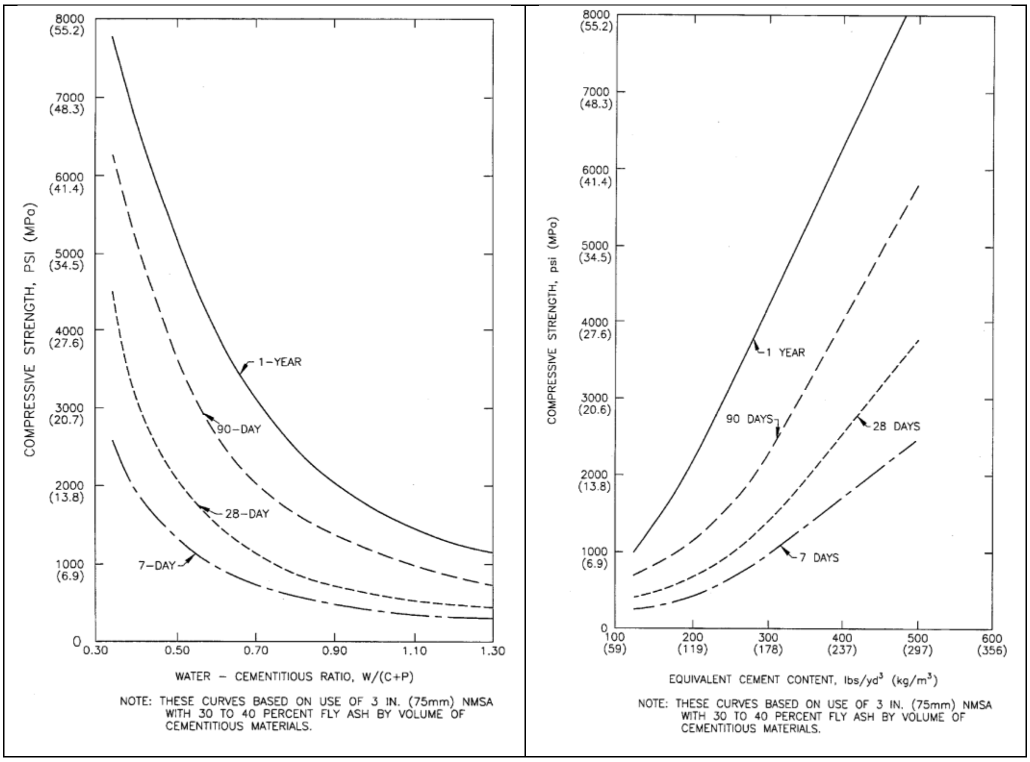


Figure 3-6 Compressive strength versus w/c and equivalent cement content (USACE, 1992)

U.S Bureau of Reclamation used the high paste method for the design of Upper Stillwater Dam. The resulting mixtures from this method generally have high proportions of cementitious material, high pozzolan and high workability yielding good lift joint strength and low joint permeability by providing sufficient cementitious material. The W/C and fly ash / cement ratios are determined in this method for desired strength level. Vebe tests are done to obtain 10 to 30 sec Vebe time for conducted to obtain consistency requirement and the optimum water, coarse and fine aggregate quantities are determined by trial batches [4].

In Japan, a method similar to proportioning CVC (in accordance with ACI) is used for RCC as well, incorporating the use of consistency meter. This method is not used widely outside of Japan due to requirement to provide consistency test equipment [1].

Finally optimum moisture and water content can be used to determine the mix proportioning of RCC samples. The desired water content is determined by moisture-density relationship of compacted specimens, using ASTM D 1557, Method D. Using various RCC mixtures having different cementitious material and water contents, the maximum density and optimum water content are determined from a plot of density-water content of the compacted specimens of each mixture. Strength testing is then carried out at each cementitious materials content [1].

3.2.5 Cementitious Material Content

RCC mixture design can be affected by many different conditions. The selected mixture design for a specific dam site can totally be misleading for another dam site. The decision should be based on realistic information related to dam size and height, foundation quality, the degree of reliable inspection expected, facing methods, climate, cooling process, thermal issues, availability and quality of materials with their cost. Use of different mix designs in a project are also possible. Abdo [16] states that due to sliding concerns during extreme loading conditions, two mixture designs were used in the dam, one in the foundation cutoff key and the other in the key. The designation for low, medium and high cementitious content mixtures are as below:

1) Lean (low cementitious content) RCC mixture : Having less than 99 kg/m^3 cementitious material
2) Medium-paste RCC mixture : Having cementitious material between 100-149 kg/m^3
3) High-paste (high cementitious content) RCC mixture: Having more than 150 kg/m^3 cementitious material

Dams built with high cementitious content mixes may have less volume but typically have a much higher unit cost and more effective cooling and quality control requirements. Lower cementitious content mixtures have lower unit cost but may require more mass. They also require special attention about good watertightness along lift joints. In the Pine Brook Dam, low cementitious content mixture was used which led more mass and conservative dam cross section but provide flexibility in aggregate selection and proportions [16]. On the other hand, according to Thang, Hung, Kyaw, Conrad,Steiger and Dunstan [17], Son La RCC dam in Vietman and Yeywa RCC dam in Myanmar were constructed within very tight schedule and high cementitious content to benefit early start of power generation and minimising river diversion costs.

High cementitious content mixtures results good cement efficiencies (strength per unit of cementitious material) when compared to CVC but lower cementitious content mixtures have even greater efficiencies along with better thermal handing such as in the Mujib Dam [21] and the Nordlingaalda Dam [58].

3.2.6 Mix Design

In this section, a batch of mixes from various RCC dams was examined in order to determine the effect of cementitious content amount and pozzolan / cementitious content ratio on the target direct tensile strength value for 28 and 90 days.

The direct tensile strength $(f_{t,d})$ values of mixes were calculated by the formula (3.2) given in Section 3.3.2.2. The splitting tensile strength $(f_{t,s})$ values were calculated by the formula (3.1) which is also given in Section 3.3.2.2. On the other hand, the compressive strength (f_c) values of mixes were taken from the literature.

The values of splitting tensile and direct tensile strengths of mixes correlates well with the ratios of splitting tensile to compressive strength and direct tensile to splitting tensile strength given in Section 3.3.2.2. The table of compressive, split and direct tensile strength values of mixes and the ratios of split tensile to compressive & direct to split tensile strengths are given in Appendix A, Table A.3 and Table A.4, respectively.

Target direct tensile strengths were assumed as 1.0 MPa and 1.3 MPa for 28 and 90 days, respectively. Results within 10% of the these levels were accepted as satisfactory in the calculations. A cost analysis was performed to see how mix design and the corresponding cost of the RCC is affected from pozzolan / cementitious content ratio. Flyash was chosen as the pozzolan used in this experiment. In cost analysis, it is assumed that the other constituents (aggregate, water and fines) of different mixes remain the same for unit cubic meter of the mixes. The costs of cement and the flyash were calculated with the 2013 year current prices of the Ministry of Public Works (109 TL/ton for cement and 16.9 TL/ton for flyash). The cost analysis table showing the cementitious content within the mix and the costs of mixtures is given in Appendix A Table A.5.

Seventeen different mixtures satisfy the target tensile strength at 28 and 90 days as given in the Appendix. These mixes have flyash percentages between 0.40 and 0.70 in the mixture. In addition, there are 4 mixes satisfying the design criteria without the use of fly ash. Cementitious material content of the mixtures reaching the target strength with flyash addition ranged from 192 to 240 kg/m^3. For mixtures without flyash the cement content was between 105 to 150 kg/m^3. These results indicate that there are two groups of mixes satisfying the target strengths. This situation is commonly observed in mix design studies. From this point on, the selection of flyash percentage for mix design is directly related with the actual cost of the design mixture, early age and long-term strength requirements and the heat generation concerns for safety of system.

When the costs of the mixes are compared, it is indicated that mixes having no flyash were observed to cost at least the same level as the other mixes since the unit price of cement is nearly seven times higher than the flyash (Figure 3-7). The use of trial mixes without flyash seem to be irrational because the flyash pushes the total cost of mix to downward.

The slope of cost curve becomes negative after the inclusion of nearly 30~40% percentage of flyash. Three Gorges Dam trial mix no.18 assumed to have a total cost of 6.84 TL*(kg/m^3) is an outlier in this study. The cost of trial mixes decrease as the flyash ratio increases, as expected. However, design mixes with high flyash ratio generally results in reduction in strength efficiency after 50~60%. Furthermore, for the design mixes that need higher target direct tensile strength value, high flyash ratios may not be suitable since pozzolans generally slow the strength development in early ages. In conclusion, the mix design for this target levels may easily include flyash material as 40~60% of the cementitious content.

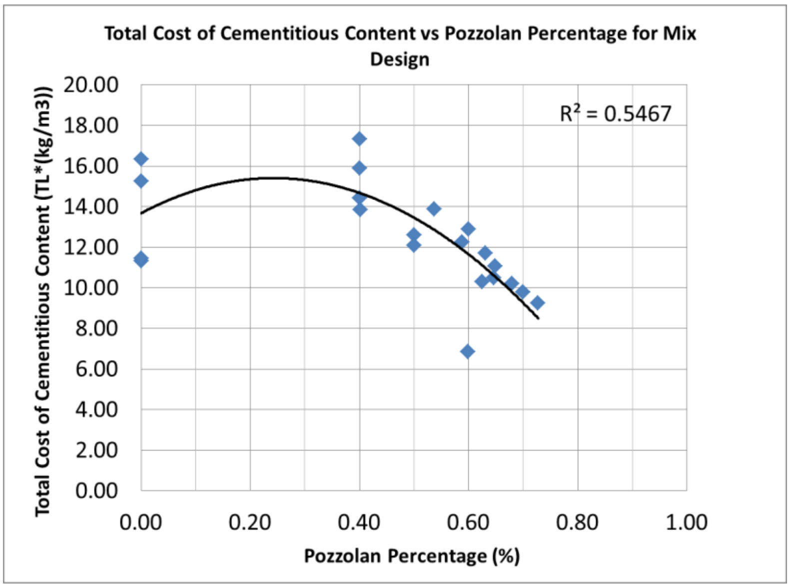


Figure 3-7 Total cost of trial mixes vs. pozzolan percentage for mix design

3.3 Material Properties

3.3.1 Compressive Strength

Compressive strength is a basic material property of RCC for design load requirements as in CVC. Almost every RCC dam project requires certain limit of compressive strength value to handle some gravity loads. However, the reason for the provision of compressive strength for RCC mixes is usually the prescription of a quality requirement (i.e. in order to reach a certain tensile strength level) as in CVC. Compressive strength is used as a measure of the durability and long term performance of RCC dams, but it is usually not a primary parameter for design: tensile strength is generally the most important and governing material property for the design of RCC dams [6].

As in CVC, the compressive strength of an RCC mixture depends primarily on the cementitious content on the mix, along with the quality and the grading of aggregates, the mixture proportion (ratio of aggregate to cementitious material), the degree of compaction and W/C ratio [2]. Compressive strength increases with increasing the amount of cementitious material within the mixture, decreasing the W/C ratio, better compaction and an increasing NMSA within the mixture. Efficiency of mixture is an important issue, for higher cementitious content RCC mixes an increase in the cement content does not lead to as much increase in the strength. Good compaction is a must, aggregates having NMSA of more than 75mm are not recommended due to segregation problems [35] [36].

Compressive strength tests are often performed at the site laboratories to design mixture proportions and determine the ratio of cementitious material and aggregates. These tests can be conducted with laboratory test cylinders or specimens cored from test fills. The compressive strength results of control cylinders from the sites of 62 dams around the world is given in Figure 3-8.

The mean compressive strengths are 8.0, 13.9, 19.7, 20.6 and 25.4 MPa and the medians for the for 7, 28, 90 ,180 and 365 days are 7.0, 12.9, 18.4, 19.0 and 25.0 MPa, respectively.

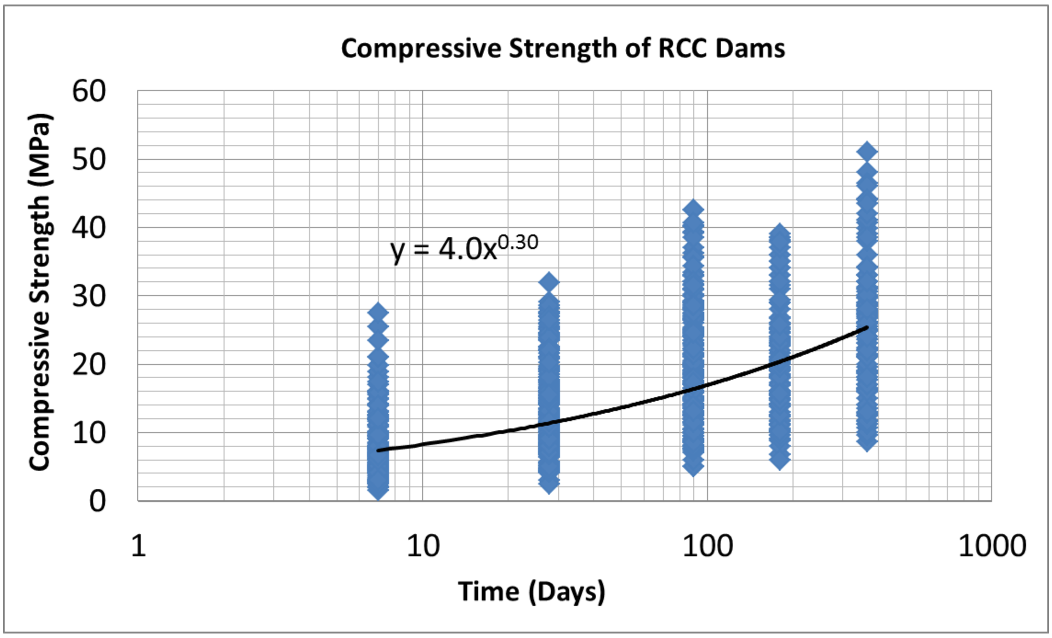


Figure 3-8 Compressive strength values for RCC dams

3.3.1.1 Strength vs. Cementitious Content

The compressive strength increases parallel to increase in cementitious content in the RCC mixture [7,31]. Hamzah and Al-Shadeedi [7] carried out a study to investigate this relation. Cementitious content can include cement replacement material like pozzolans, fly ash, blast furnace slag, etc… A study conducted by Canale, Ozen and Eroglu [37] for Aladerecam Dam shows an increase in the 90 day compressive strength from 9.4 to 10.2 MPa for an increase of trass from 70 to 75 kg/m^3 in the mixture.

The variation of the compressive strength at 28 and 90 days are shown in Figure 3-9 and Figure 3-10 with respect to the cementitious material content in the mixture for a range of dam sites around the world. The water content of different mixtures are identical within each dam. An increasing trend in the compressive strength with respect to cementitious content amount in the mixture is easily discernible. However, the large variation (as compared to CVC) in the compressive strengths obtained for similar cementitious content is notable. As high as 45 MPa compressive strength was obtained for the Nordlingaalda Dam for roughly 200-210 kg/m3 cementitious material content. Only 8 MPa was obtained for the Upper Stillwater Dam with slightly higher cementitious material content. A detailed summary of the data shown in the figure is given in Appendix B Table B.1 [30, 140, 141, 39, 51, 58, 21, 28, 142, 143, 144, 145, 41, 146, 53, 139, 57, 26, 40, 68].

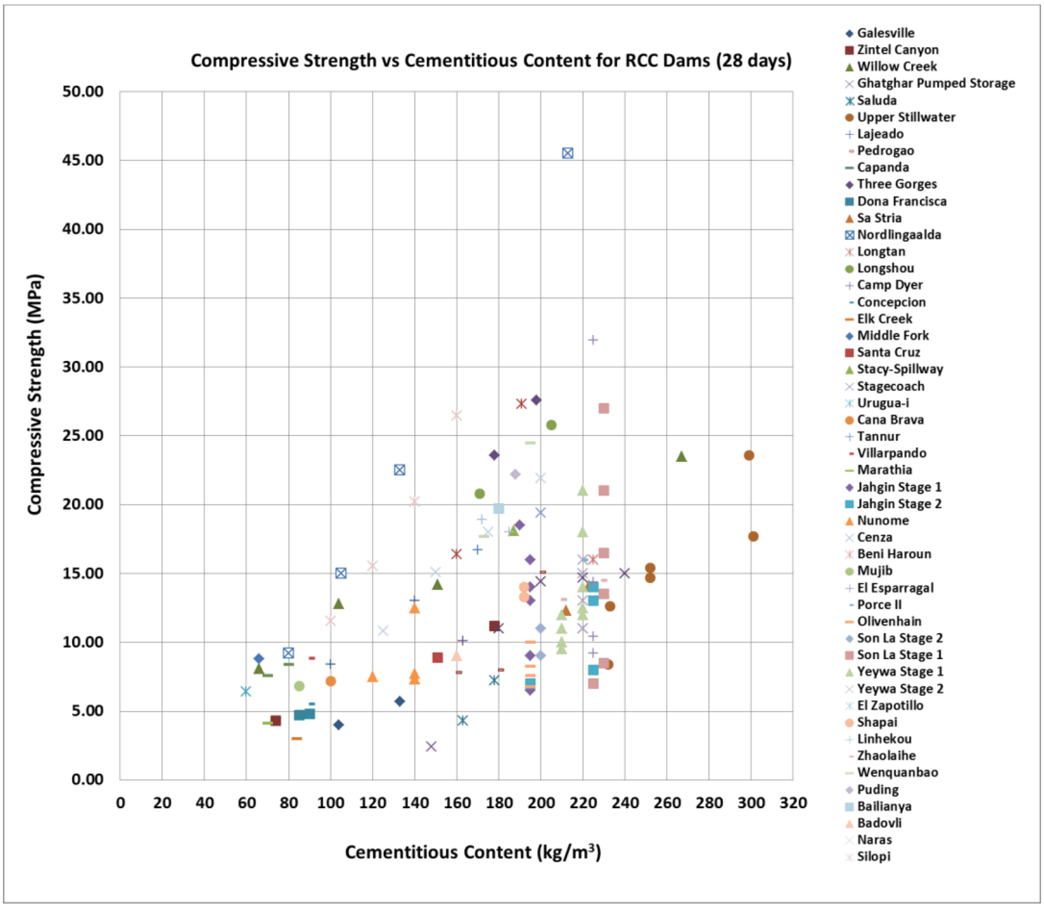


Figure 3-9 Compressive strength versus cementitious content for RCC Dams (28 days)

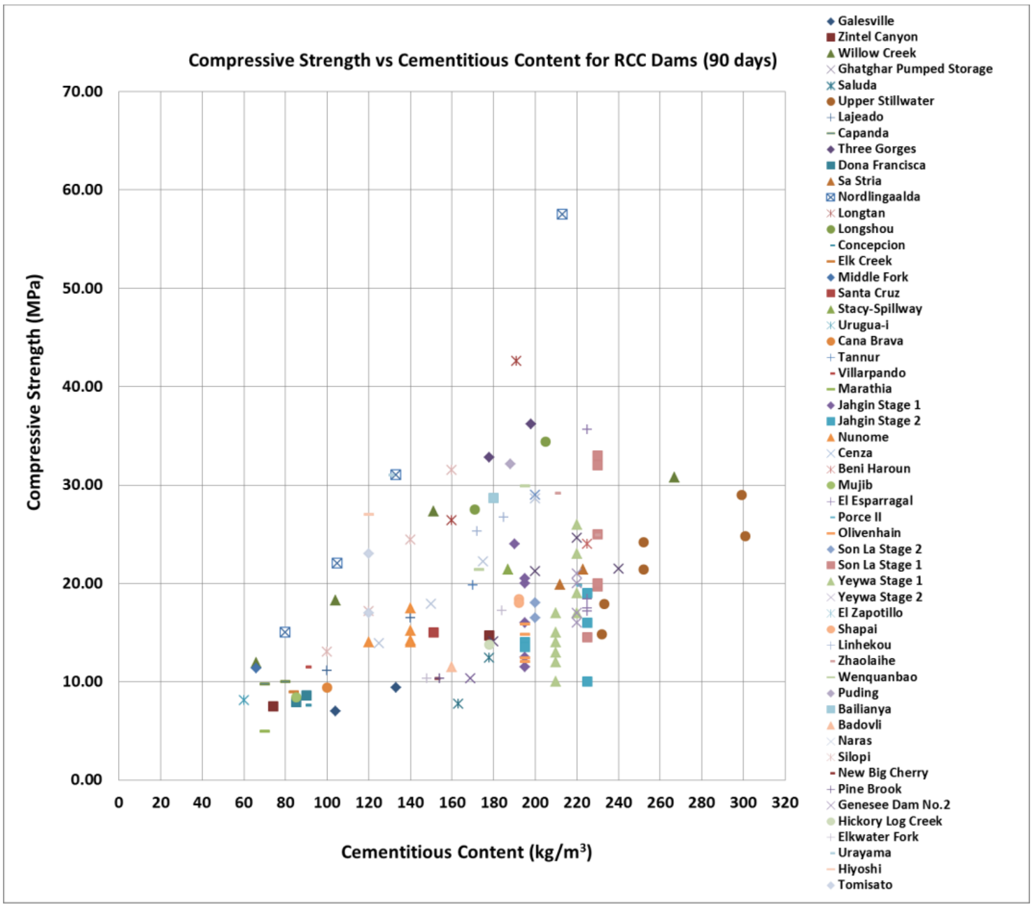


Figure 3-10 Compressive strength versus cementitious content for RCC Dams (90 days)

RCC mixtures usually gain strength with increasing cementitious content but there seems to be a reduction of efficiency (MPa/(kg/m^3) of cement) with increasing cementitious content. In other words, less strength is gained per kg of cementitious material as more cement is added to the mix. The quality of pozzolan used in the mixture may even lead worse situation in terms of strength efficiency [21]. For the Mujib Dam, the quality of the pozzolan was not sufficient for the high cementitious content mixture. The most efficient mixes had lower cement contents and lower pozzolan or no pozzolan.

The Figure 3-11 shows the compressive strength efficiency versus cementitious content (cement and pozzolan) values of RCC dams for 28 and 90 days from the collected data. It shows that the average efficiency is about 0.10 with a variation between 0.05 to 0.20. There appears to be some reduction in efficiency for mixtures with cementitious content higher than 200 kg/m^3. The table of data is shown in Appendix B Table B.2.

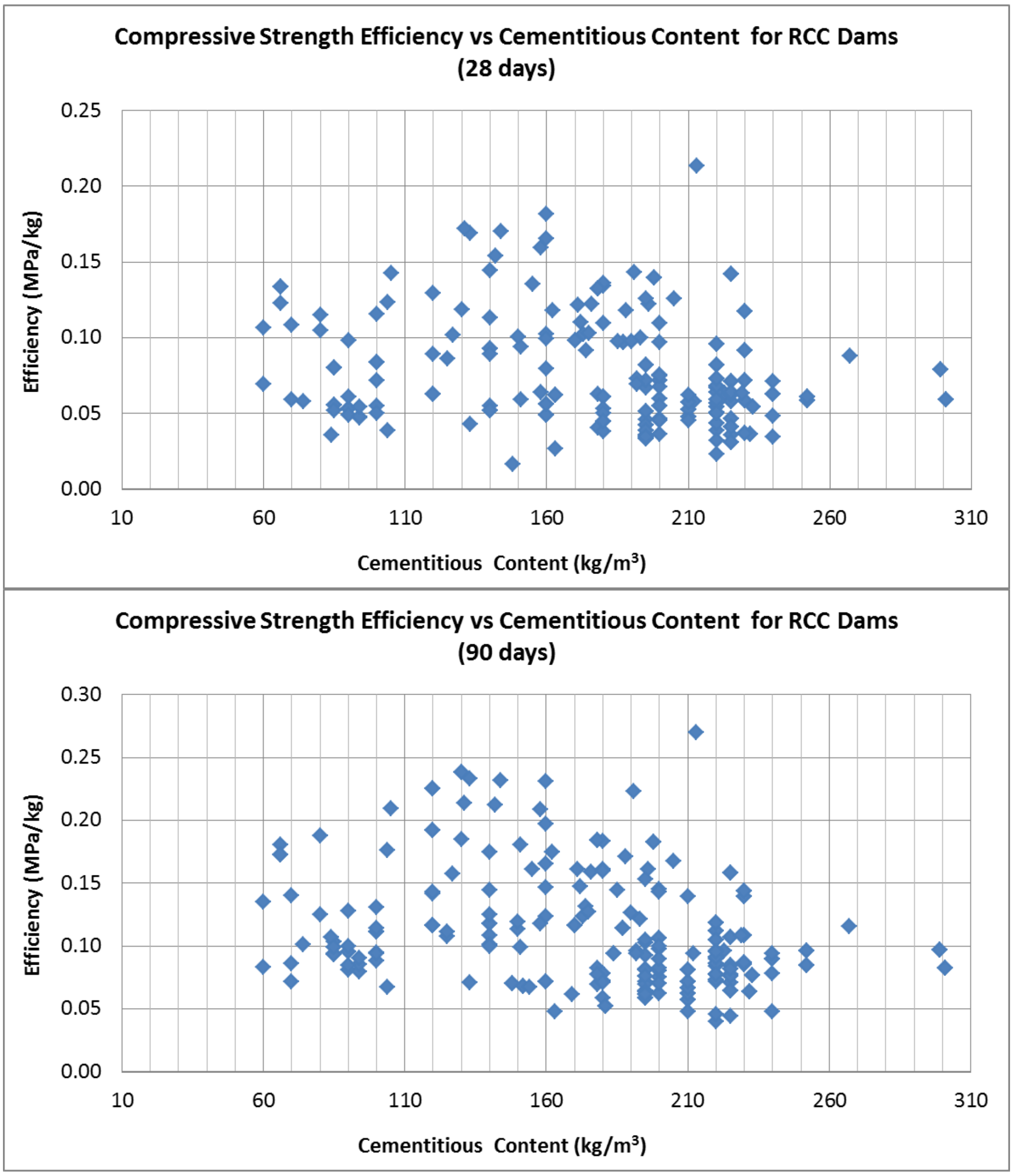


Figure 3-11 Compressive strength efficiency versus cementitious content for RCC Dams

3.3.1.2 Strength vs. W/C Ratio

The compressive strength increases with decreasing w/c ratio if proper compaction is done. The function of w/c ratio is similar to what happens for CVC. Figure 3-12 illustrates this situation for 28 day compressive strength development of some RCC dams [30, 140, 141, 39, 51, 58, 21, 28, 142, 143, 144, 145, 41, 146, 53, 139, 57, 26, 40, 68]. The table of data is shown in Appendix B Table B.3.

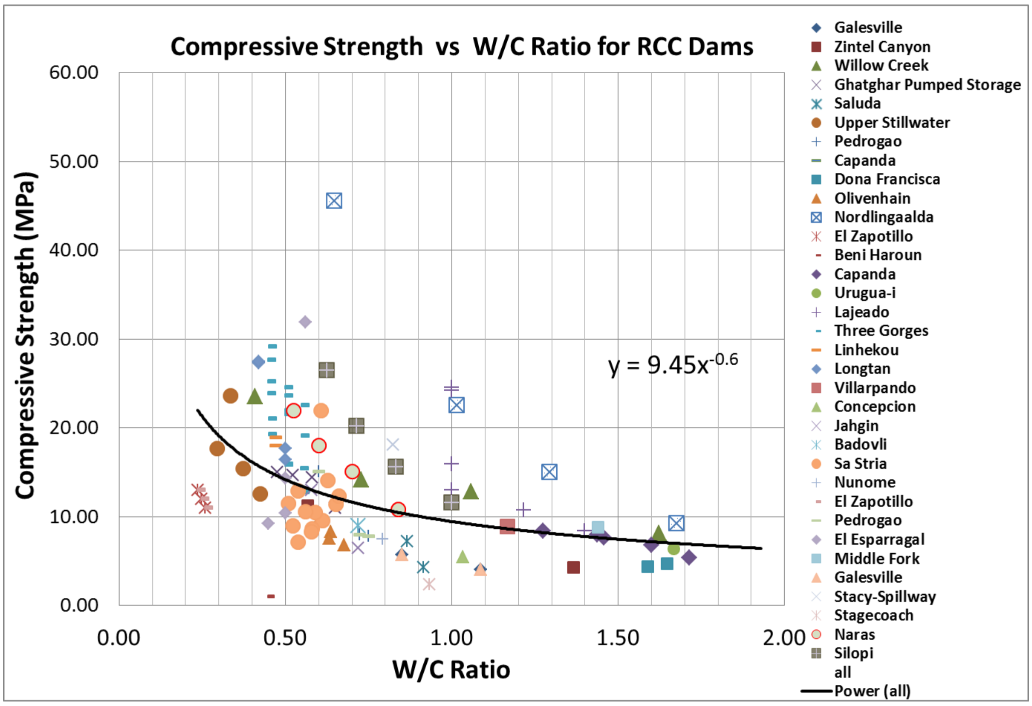


Figure 3-12 Compressive strength versus w/c ratio for RCC Dams

3.3.1.3 Strength vs. Pozzolan/Cement Ratio

Pozzolan replacement ratio in the RCC mixture play an important role on the compressive strength gain within the time. Fly ash is one of the most efficient types of pozzolan in terms of strength development. There are many studies investigating the optimum ratio of fly ash replacement ratio in the RCC mixture to have the desired design strength in a most economical way.

The cement content could be replaced by fly ash conveniently for RCC material provided that short term strength is not a major design variable. Cement content can be replaced by as much as 70% by fly ash. However, most studies show that there is an optimal replacement ratio for which the maximum strength with replacement could be obtained [36, 9, 7,10]. These optimal ratios were obtained to be 30% [9], 20% [7] and 50% [10] fly ash replacement. The variation in the strength for 7, 28 and 91 days is given in Figure 3-13 for different mix designs [9]. As given in the figure, for the long term strength 30% fly ash replacement is optimal[9]. While only long term strength was optimal in [9], Figure 3-14 shows the results of another study in which the compressive strength at optimum value of metakaolin/cement is consistently higher from other mixes at even 7 days [7].

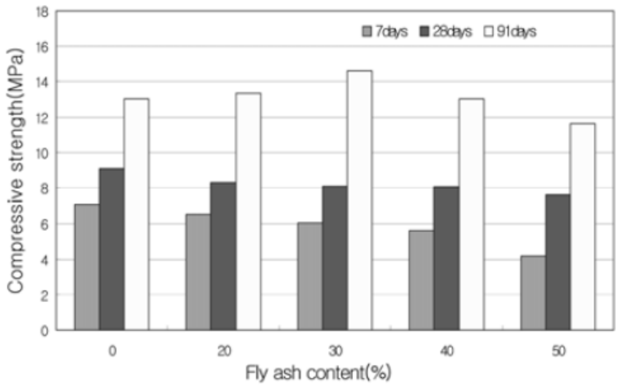


Figure 3-13 Compressive strength with fly ash replacement ratio [9]

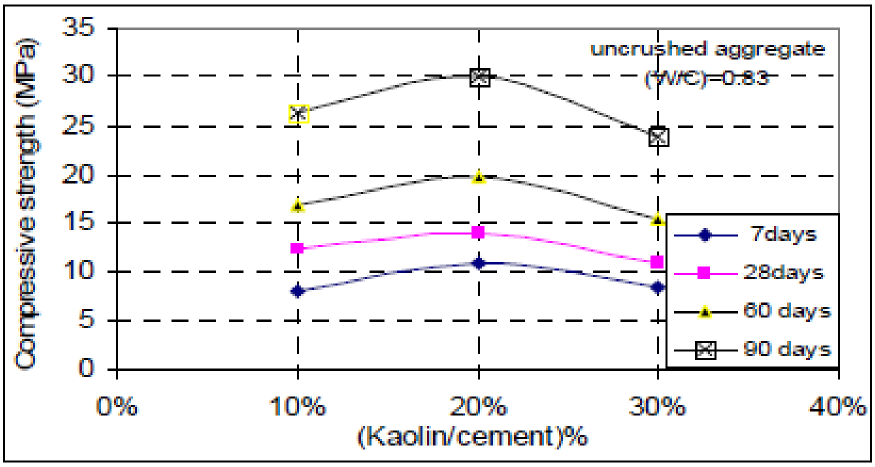
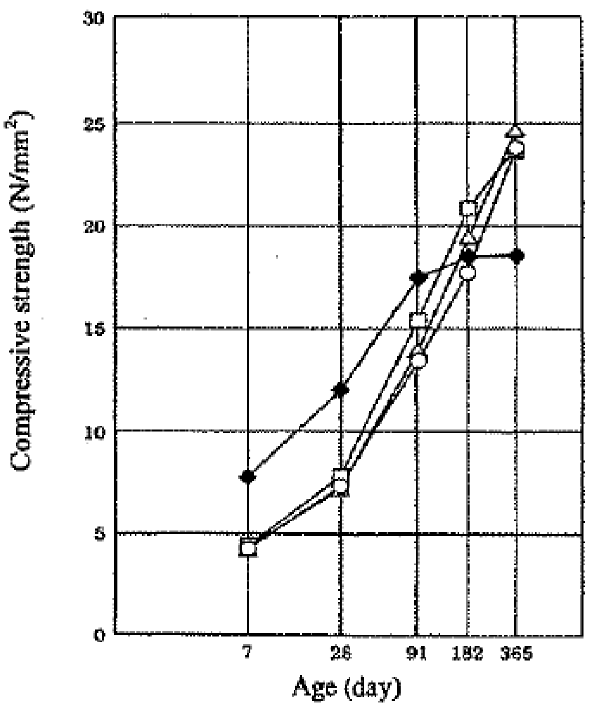


Figure 3-14 Variation in compressive strength with (metakaolin/cement) % [7]

The increase in the ratio of fly ash to cement delays strength development of RCC in the short term. Higher fly ash content decreases early strength [9,38] but, in the long term pozzolan increases RCC ultimate strength seriously. According to Dolen [41], this is because of the fact that fly ash is quite reactive in the long term strength gain. In the Upper Still Water Dam which consists of 70% fly ash in the design mix, within first 28 days the compressive strength reached only 30% of the 1 year value. A typical example of strength gain in mixtures can be seen in Hino, Jotatsu and Hara [38]. As shown in Figure 3-15, until 28 days the strength gain of the mixture containing 35% fly ash has lower rate than the one without fly ash inclusion. However, after 28 days the rate of increase of compressive strength of mixture with 35% fly ash content gets steeper while the rate of increase of mixture without fly ash goes down gradually. After 180 days, the compressive strength of the mixture with 35% fly ash goes up of the mixture without fly ash.



Mark	Mix	Slump	$C+F$	$F/(F+C)$	W
◆	A-1	3±1	140	0	117
□	A-2	3±1	140	30	113
△	A-3	3±1	140	35	111
○	A-4	3±1	140	40	107

Figure 3-15 Result of compressive strength test

Figure 3-16 and Figure 3-17 show the compressive strength variation for RCC mixtures with different pozzolan percentages for the same total cementitious content values of RCC dams for 28 and 90 days from the collected data. The figures show that the compressive strength of RCC mixtures decreases with the increasing percentage of pozzolan in the mixture. The percentages of 30~40% are generally seem to be ideal for optimum compressive strength.

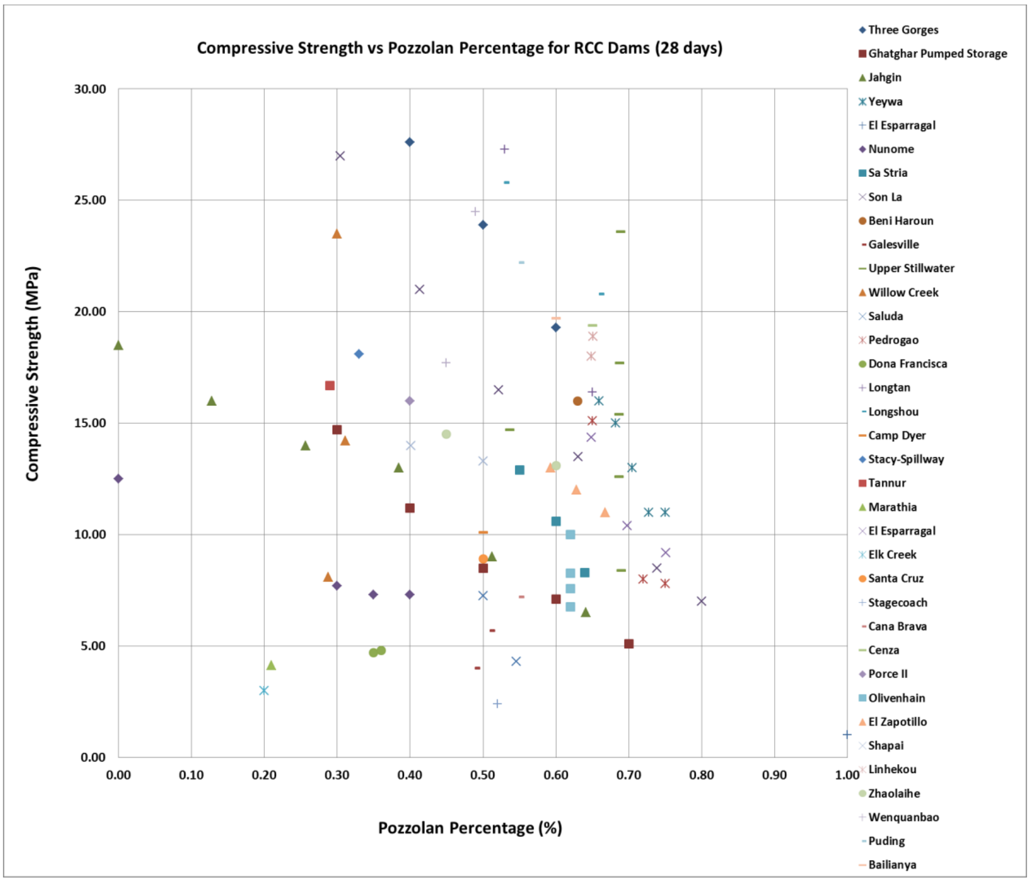


Figure 3-16 Compressive strength versus pozzolan percentage for RCC Dams (28days)

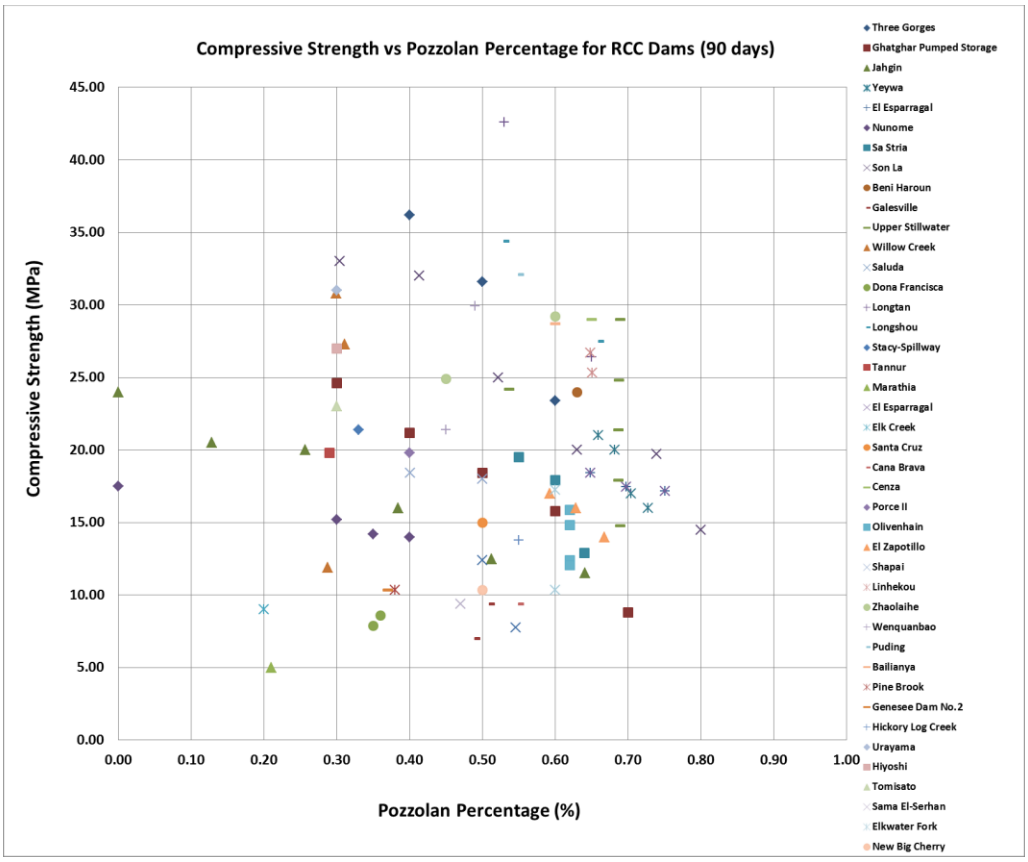
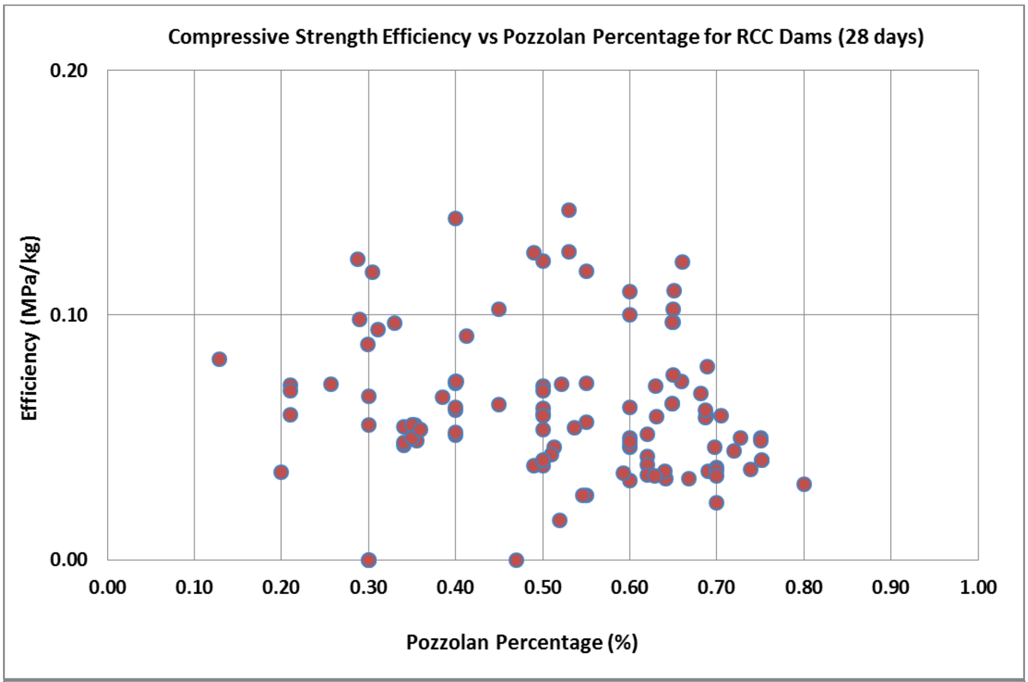


Figure 3-17 Compressive strength versus pozzolan percentage for RCC Dams (90 days)

The Figure 3-18 shows the compressive strength efficiency of RCC dam mixtures with different pozzolan percentages for 28 and 90 days from the collected data. The figures show that the efficiency of RCC mixtures decreases with the increasing percentage of pozzolan in the mixture. The percentages of less than ~50% pozzolan have greater efficiency values than the ones having more than 50%.



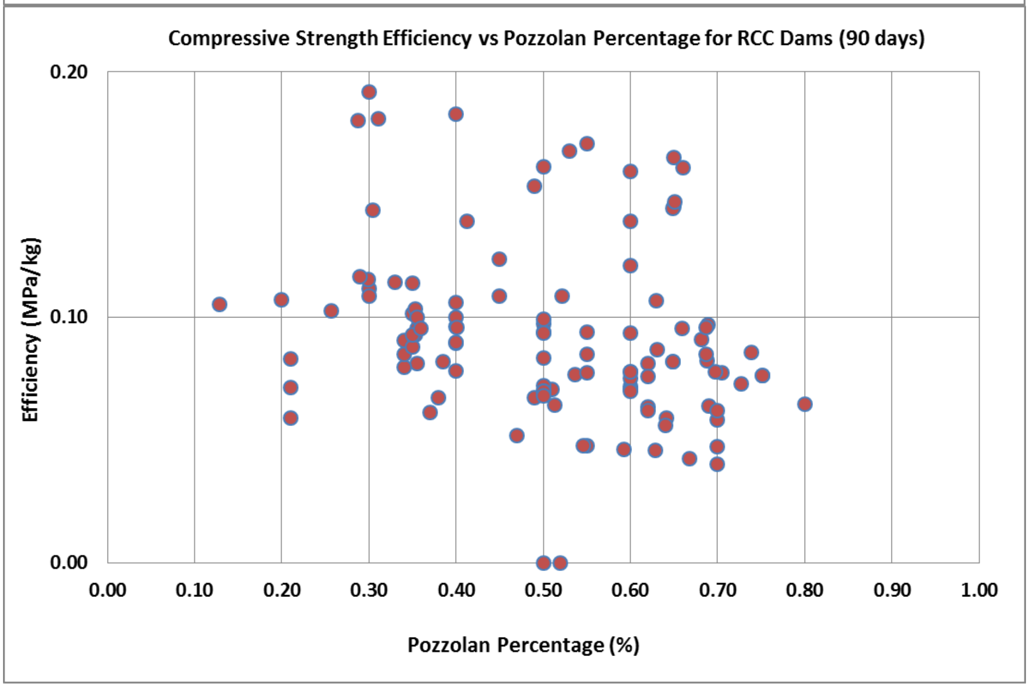


Figure 3-18 Compressive strength efficiency versus pozzolan percentage for RCC Dams

It should be kept in mind that each project may require a different design strength value depending on design age, geometry of the dam, site conditions and seismicity of the location. Some projects may handle the design strengths achieved by design mixtures having high percentages of fly ash content. For example, the Pedrogoa RCC Dam required 12 MPa design compressive strength after choosing high quality aggregate instead of low quality aggregate in the design mixture and changing the design age of 90 day with 1 year. As a consequence, the designer could be able to use 75% of fly ash replacement in the design mixture which meets the design compressive strength [39]. Similarly, in Ghatghar RCC Dams the design compressive strength of 15 MPa at 90 days is required. Design mixture of containing 220 kg/m^3 cementitious content with a 60% fly ash replacement is economical and satisfactory in terms of strength requirements [40].

Finally, it should be mentioned that there are exceptions to the general trend of long term strength gain for mixtures with high fly ash replacement. In the Willow Creek Dam, adding fly ash to the test mixture did not yield any strength gain in the long term [2]. Therefore, one should keep in mind that the quality of pozzolan may play an important role in the long term strength development.

3.3.1.4 Strength vs. Pozzolan Type

The type of pozzolan used in the mixture affects the development of compressive strength significantly. Farias, Hasparyk, Liduario, M.A.S. Andrade, Bittencourt and W.P Andrade [8] carried out a study using different types of pozzolans with different amounts to evaluate the changes in RCC mixture properties and obtain a durable mixture. The types of pozzolanic material used were fly ash, natural pozzolan, metakaolin, rice-husk ash, powdered aggregate, blast furnace slag and silica fume.

For all the mixtures, 100 kg/m^3 of Type II Brazilian portland cement was used along with 155 kg/m^3 water. The results of compressive strength for 90 days is shown in Figure 3-19. It is shown that adding pozzolans to RCC mixture improves the compressive strength significantly. Fly ash and blast furnace slab appear to be the most effective additives for increasing the compressive strength of the mixture. A similar study was conducted by Malkawi, Shaia, Mutasher and Aridah [31] to in order to compare the contribution of fly ash and natural pozzolan to compressive strength of RCC mixtures. Fly ash was shown to be more effective compared to natural pozzolan in yielding higher compressive strength in later ages due to its higher silica content increasing the pozzolanic reaction between the cement and fly ash. The contribution of phosphorus slag replacement was investigated by Guangwei [42] leading to the conclusion that in comparison with the fly ash replacement, RCC mixtures with phosphorus slag have lower early strength but higher long term strength.

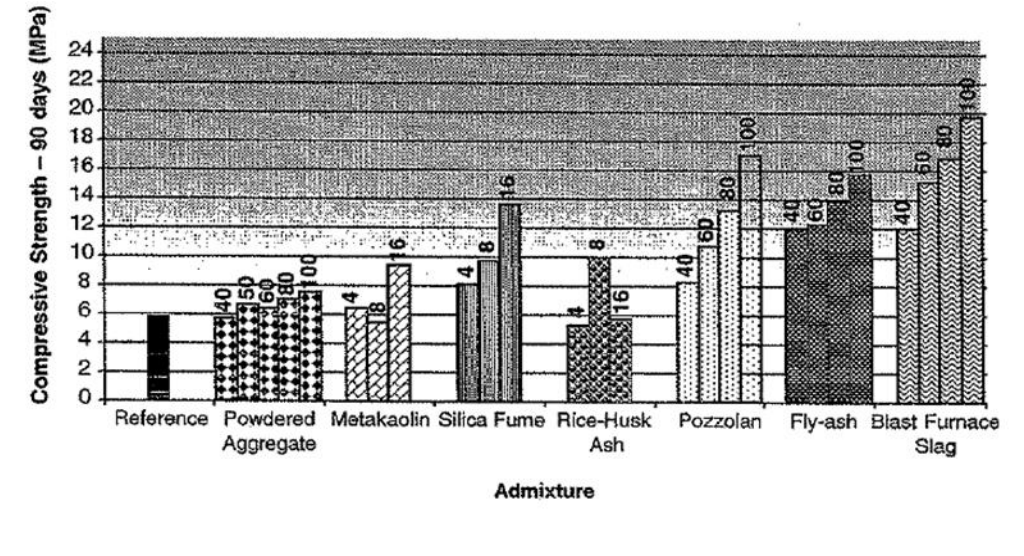


Figure 3-19 Compressive strength of RCC [8]

3.3.1.5 Strength vs. Fine Content

The natural or manmade fines are very important for low cementitious RCC mixes to provide adequate paste and fill the void spaces for better compaction but there is no evidence that the fine content has positive effect on strength. The pulverized or powdered aggregates may reduce the strength development of RCC mixture very slightly or the strength develops almost the same while improving the workability of the mixture by filling effect [43][44]. According to Gaixin and Xiangzhi [45], the limestone powder has no pozzolanic activity so that does not increase strength but workability and compactibility are improved significantly. However, according to Schrader [2], some type of fines may increase the strength of low cementitious content mixtures. Figure 3-20 shows the effect of fines on strength increase of Willow Creek Dam mixture:

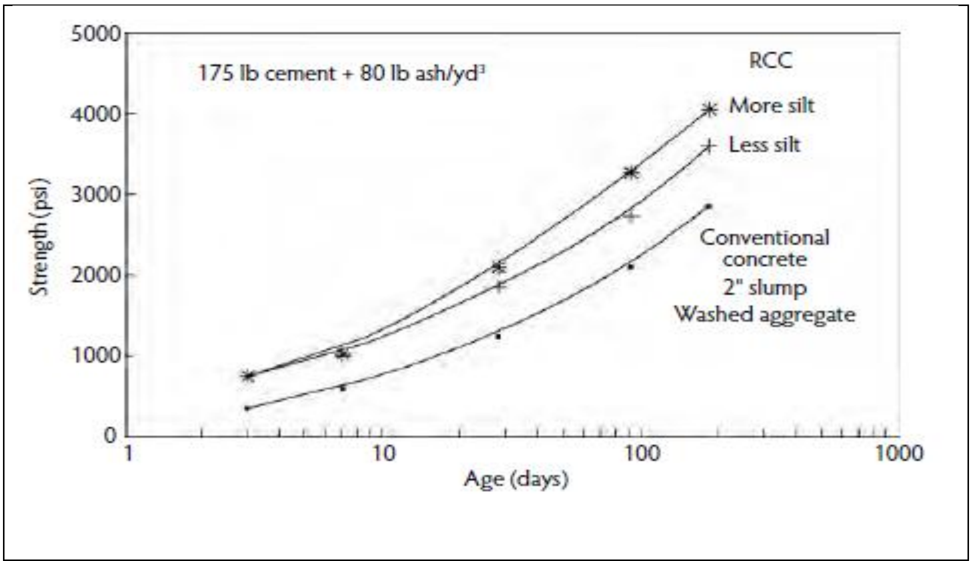


Figure 3-20 Effect of fines on strength, Willow Creek RCC Dam [2]

3.3.1.6 Strength vs. Compaction

The degree of compaction has a great influence on the compressive strength of RCC in both laboratory and in core samples from in-situ construction. Since RCC has dry consistency, compaction is more affordable than CVC. In the field, the sufficient number of passes should be performed by vibratory roller to achieve the desired strength. Tsukada [48] states that in Ueno RCC Dam, the core samples taken from the lower parts of the horizontal lifts exhibited lower strength than the ones from near surface of the lift due to insufficient compaction caused by the depth. Therefore, the lower parts of the lifts should be passed by roller as much as possible during spreading to compensate the reduced effect of compaction due to increasing thickness of the lift. For laboratory specimens, enough energy should be transferred to specimen to achieve full compaction, if not strength will not rise to the required level due to high void content. A well compacted RCC mix should not have more than 1.5 % air void. According to Gagne, Houehanou, Lupien, Prezeau and Robitaille [50], a void content higher than 4% lowers the compressive strength although it improves the workability. However, they concluded that a 1% to 4% void ratio can decrease the amount of total cementitious content needed without penalizing the workability or strength. On the other hand, 5% of air void due to poor compaction was shown to result in a 30 % of strength loss in [3][46][49].

For in-situ situation, compaction of RCC should be started after placement and finished within 15 minutes. In order to elongate the work time of RCC, the low cementitious content mixtures or different pozzolan types can be selected [47]. The appearance of fully compacted concrete is dependent on mixture content. Mixtures having wetter consistency causes visible pressure waves in front of the roller. Generally four to six passes of a dual drum 10-ton vibratory roller achieves the desired density of 98% for RCC lifts between 150 and 300 mm [1][2].

3.3.1.7 Strength vs. Curing

Curing is a very important process for RCC mixtures because, the W/C ratio of RCC is low in general so that no free water is available in the mix. After spreading and compaction of the RCC lift, drying should be prevented in the first seven days, if not low strengths are observed [46]. A laboratory test carried out by Nanni [52] to investigate the effect of air-drying and moist-curing on the RCC specimens' compressive strength development shows that while the compressive strength increases with the exposure time and number of curing cycles, it reduces with the air-drying of the specimen especially on the surface of RCC. The curing of laboratory specimens (in an oven) to obtain an accelerated strength gain was investigated by Pauletto, Dunstan and Ortega [51] leading to a method to extrapolate strength of cured mixes from early age RCC specimens.

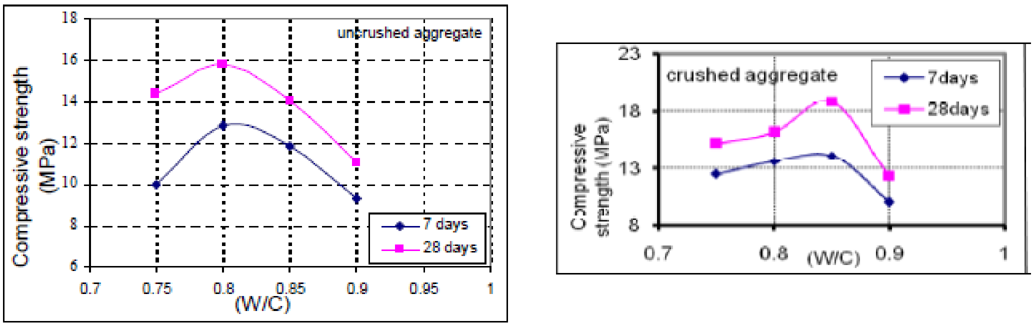
3.3.1.8 Strength vs. Aggregate

The compressive strength is directly influenced by the quality of aggregate. The high quality aggregate should be procured if it is not available on site when high strength is desired. However, the use of low quality aggregate can be tolerated in mass concrete applications if strength is not the principal concern within dam body. In the past, some dams constructed with low strength aggregates showed good creep rates, elastic moduli and tensile strain capacity. In Wyaralong Dam, on-site poor quality sandstone is used because of the low strength need [14]. Iin the Koudiat Acerdoune RCC dam Bouyge and Forbes [15], .the desired design strength was achieved with weak alluvial aggregates in the absence of other better and economical options.

The shape and size of the aggregate affects the compressive strength as well. The water demand of the RCC mixtures increase when the aggregates are more rounded and flaky than usual. The use of rounded and flaky aggregates in Yeywa Dam resulted in low strength than expected [53]. The optimum percentage of coarse and fine aggregates should be chosen in order to balance W/C ratio. Fine aggregate and fine particle contents prevent the strength loss due to high water demand because of aggregate voids. A better gradation of aggregates leads to a greater compressive strength in the RCC. In the Pedrogao RCC Dam (Ortega, Bastos and Alves [39]) washing and increasing the number of sizes of aggregates from two types to four types, which enabled a better gradation curve filling the grading gaps, led to a greater compressive strength in the mix design.

The use of crushed and uncrushed aggregates directly affects the mechanical properties of RCC mixtures. Hamzah and Al-Shadeedi [7] carried out an experimental work to study the effect of aggregate type on mechanical properties of RCC mixtures. Using crushed aggregate increased the interlocking between particles of aggregate and gave better compressive strength than with uncrushed aggregate.

Figure 3-21 shows the compressive strength developments of two aggregates types. The effect of the aggregates on the compressive strength was observed in three full scale trial mixtures of Yeywa RCC Dam. The shape of crushed aggregates has been found to influence the water demand and as a result compressive strength significantly. Production of good shape and well graded aggregates lowers the water demand and increases the compressive strength [53].



(a) uncrushed aggregate **(b)** crushed aggregate

Figure 3-21 Variation in compressive strength with W/C ratio for 7 and 28 days [7]

3.3.2 Tensile Strength

Tensile strength is arguably the most important mechanical property of RCC since it is very important for acceptable behavior during seismic and thermal loading-unloading of RCC dams. The tensile strength is affected by several factors,namely, cementitious material content in the mixture, aggregate quality,grading,bond between paste and aggregate, W/C ratio and air voids within the RCC matrix. Additionally, bond characteristics, the condition of the lift surface, treatment and test methods are other factors influencing the tensile strength of RCC [6].

There are two major type of tensile strength : direct tensile strength and indirect (split) tensile strength. Direct tensile strength means that the load is applied to the specimen directly: the speciment is subject to pure uniaxial tension. Direct tensile strength tests results may be assumed to represent the minimum tensile properties of the concrete. These tests are difficult to conduct for concrete since they are affected by drying and microcracking of specimens as well as test setup and procedures. Direct tensile strength tests tend to produce higher variability test results when compared to split tension tests.

Direct tensile strength is about 65 to 75 percent of the splitting strength [3]. It is difficult to apply uniaxial tensile force to the full circular cross section without any torsion or bending. In order to solve these problems related to direct tensile testing, Olivares, Navarro and Ausin [29] used a modified test setup and realized that the failure of the specimen near one of its ends is an indicator of poor direct tensile strength testing. Tests with these type of failures underpredicts the direct tensile strength of RCC specimens. Similarly, Malkawi and Mutasher [27] made a test setup to predict the direct tensile strength of RCC dams. Direct tension test is also used to evaluate the tensile strength of lift joint. Lift joint direct tensile strength tests should be done on cast specimens and/or cores from test placement sections to provide results for final design [19]. The core testing study was done at Elk Creek,Willow Creek, Cana Brava and Upper Stillwater , Aladerecam, Mujib, Olivenhain, Beni Haroun, Porce II, Capanda and La Brena II Dams [65][66][41][37][21][67][68][28][26][69]. Li, Zhang F., Zhang W. and Yang [25] conducted a direct tensile test on core specimens extracted from a practical RCC dam. The results showed that the direct tensile strength of RCC matrix is a function of the maximum size of aggregate to the characteristic dimension of the specimen. Besides that, the anisotrophy of the RCC mixture due to alignment of coarse aggregate inside affects the tensile strength taken from vertical and horizontal cores [19]. A summary of the attained direct tensile strength values at 7, 28, 90, 180 and 365 days from different projects are presented in Figure 3-22. Direct tensile strength approaching 3.00 MPa value was obtained for the 17 project at 90 days. Tensile strength values as low as 0.3 MPa is also observed. It can easily be said that an average of 1.5MPa of direct tensile strength is obtained for both 28,90 and even 360 days.

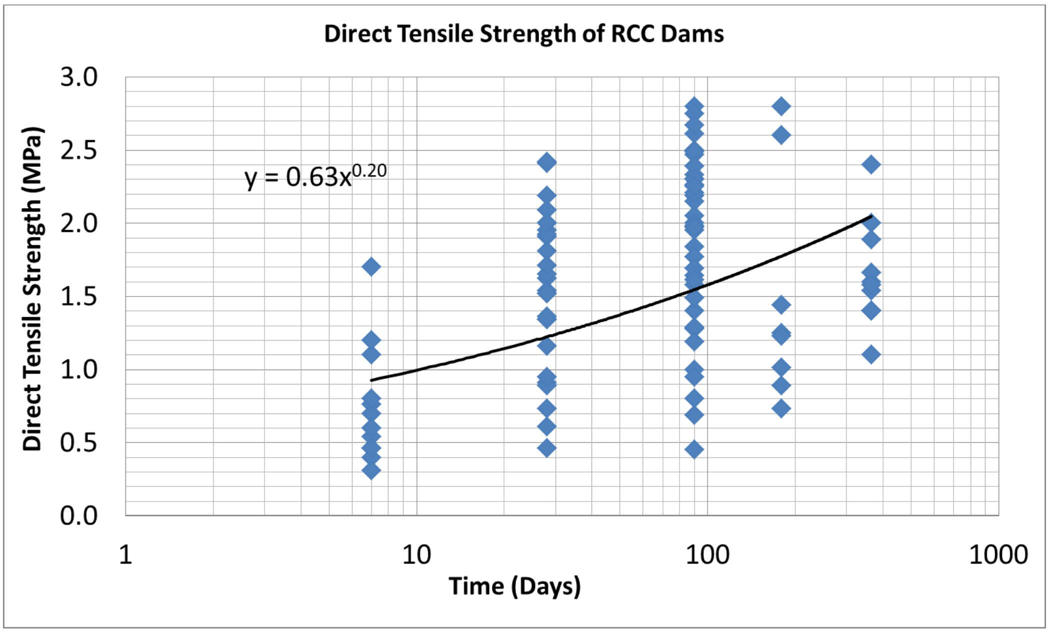


Figure 3-22 Direct Tensile Strength of RCC Dams

Split tensile strength test is usually the preferred tensile strength testing methodology due to relatively simple test setup and consistency in test results. Details of split tensile strength testing is not provided here as it is the conventional procedure with which CVC is usually tested. As mentioned before, split tensile test usually overpredicts the tensile strength, and therefore should be adjusted by a strength reduction factor to reflect results that would be obtained from direct tensile tests. The split tensile strength values (indirect tensile strength) obtained for different RCC dams projects around the world are given for 7, 28, 90, 180 and 365 days in Figure 3-23. Detailed list of the projects and the corresponding tensile strength values are given in Appendix B Table B.7.

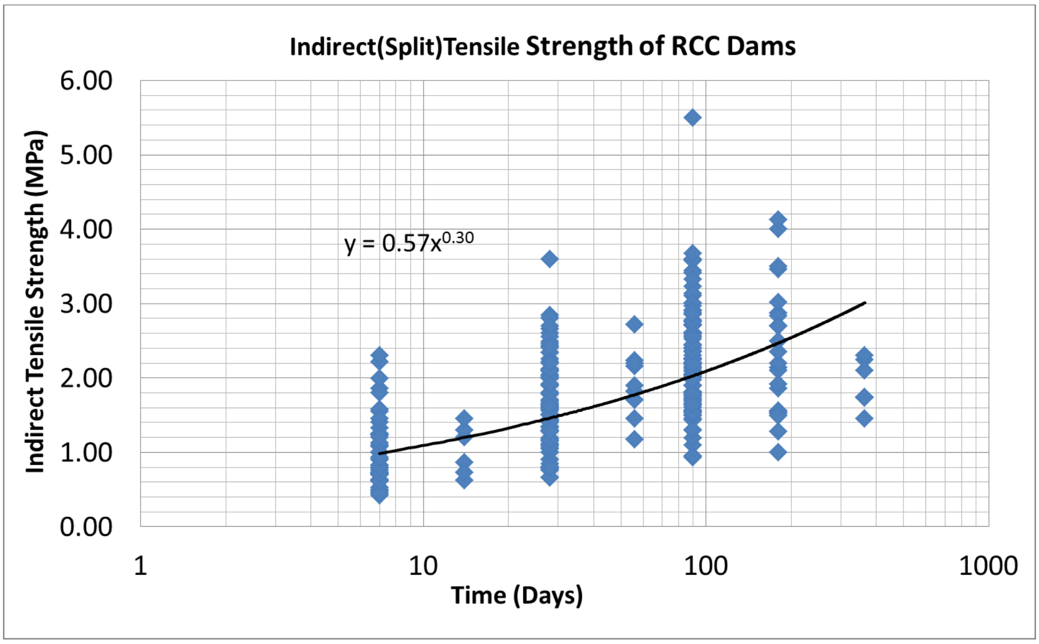


Figure 3-23 Indirect Tensile Strength of RCC Dams

3.3.2.1 Tensile Strength vs Cementitious Content

Cementitious material content in RCC is comprised of cement and fly ash. It is well known that the amount of cementitious material content affects the strength of the material directly: Low cementitious material content leads to low tensile strength for an RCC mix. However, even with a low cementitos content, it is possible to obtain decent tensile strengths from RCC material in the long term. For the Capanda RCC Dam, cores made with 70 kg/m^3 cementitious content had tensile strength of 1.66 MPa in 365 days whereas, cores with 80 kg/m^3 cementitious content had 1.89 MPa [26].

A typical example of the increase of the split tensile strength with more cement content is given in Figure 3-24 [31]. A definite increase of the final strength of the material with increasing cement content is seen.

Notably, increasing cement content directly affects the tensile strength, from 90 days onwards, a significant increase in the tensile strength was not seen. Use of fly ash on the other hand leads to a significant increase in the strength with the aging of the material. This well known effect is also evident for the tests conducted for the Big Haynes RCC dam as shown in Figure 3-25. A mix design with no fly ash content leads to the plateau of design strength near 90 days, while a significant increasing trend in the strength for mixtures with flyash content is clearly evident. Moreover, a greater increase in the strength is shown with a greater fly ash content. Although the initial strength of a mix with significant flyash replacement is much lower than a mix with %100 cement, the strength “catches up” in the long term.

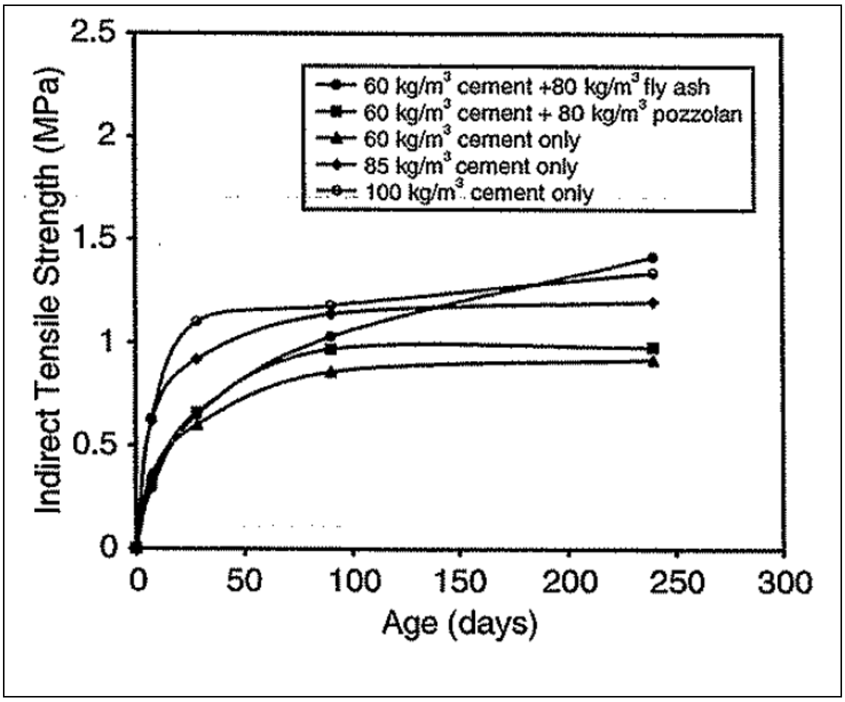


Figure 3-24 Split tensile strength test results [31]

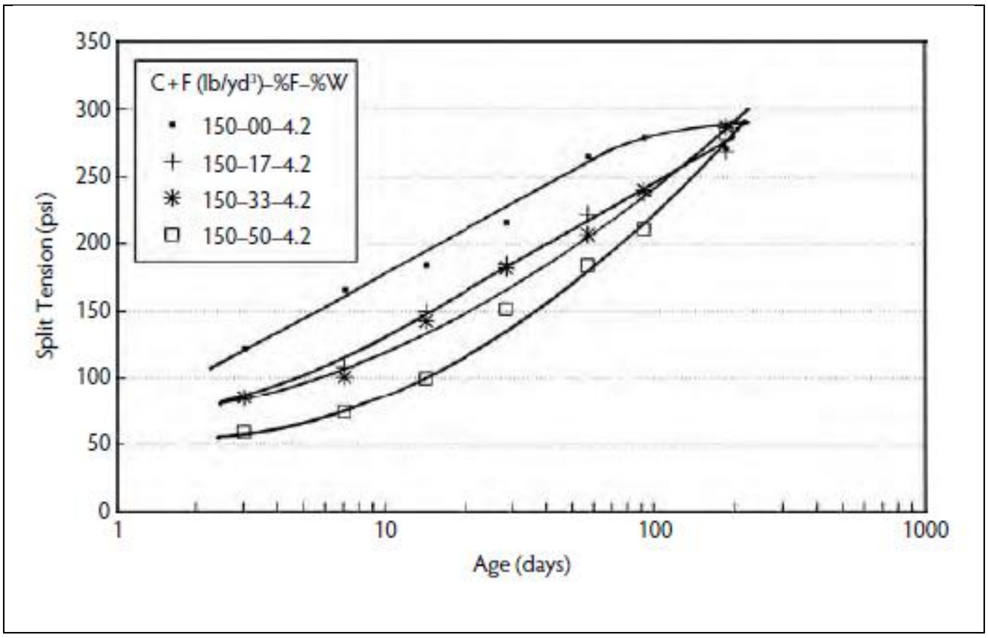


Figure 3-25 Split tension vs. percent fly ash [2]

While a replacement of cementitous material with flyash content is advantegous for long term gains in the strength, the study conducted for the Big Haynes RCC dam as shown in Figure 3-25 should not be interpreted to point out that a similar cementitious material amount leads to a similar strength in the long term regardless of the percentage of flyash replacement. A study conducted by Park, Yoon, Kim and Won [9], showed that an optimal flyash content may be an issue to reach the highest tensile strength for a design mix design. Five mixtures with 0, 20, 30, 40 and 50% replacement ratios of cement with fly ash were prepared and tested for tensile strength at 7, 28 and 91 days. A 50% difference in the final strength could be seen between the mixtures with 30 and 50% fly ash replacement in this case, with more flyash replacement leading to lesser of the strength values as shown in Figure 3-26.

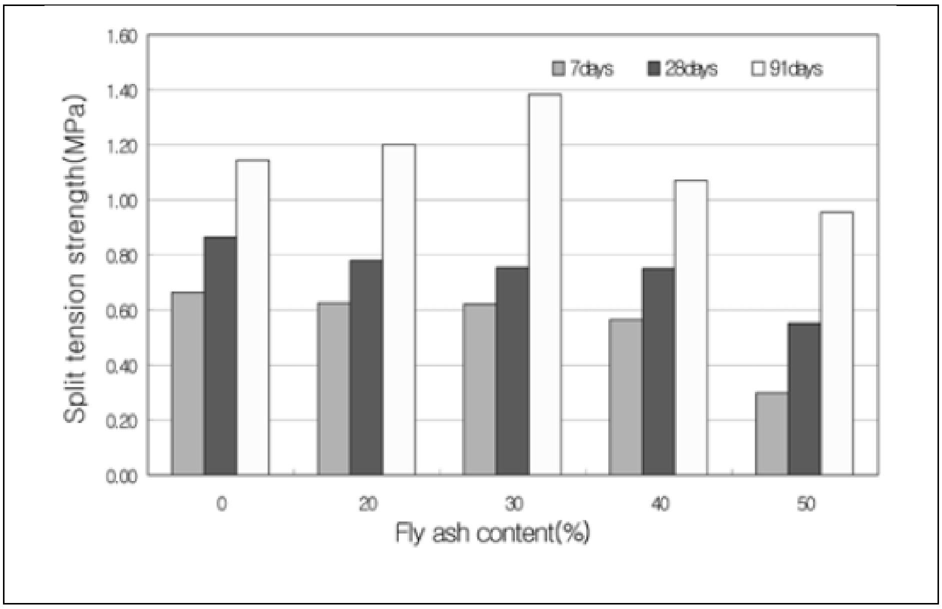


Figure 3-26 Splitting tensile strength with fly ash replacement ratio [9]

Use of other cementitous materials instead of fly ash has also been tried given the recent high costs for obtaining flyash material either due to scarcity near the site or transportation logistics. Farias, Hasparyk, Liduario, M.A.S. Andrade, Bittencourt and W.P Andrade [8] carried out a study using different types of pozzolanic material in this regard to evaluate the changes in RCC mixture properties. Powdered aggregates, metakaolic, silica fumes, rice-husk ash, pozzolan and blast furnace slag was used along with flyash in this study. Blast furnace slag and perhaps pozzolanic replacement yielded comparable strengths with flyash replacement in the RCC material, however, other choices was less than satisfactory. The split tensile strength values for these mixes are shown in Figure 3-27. The fly ash and blast furnace slag have especially superior results in terms of split tensile strength due to their dense microstructure and high pozzolanic activity characteristics [8]. Another test done by Malkawi, Shaia, Mutasher and Aridah [31] to investigate the comparison of the contribution of fly ash and natural pozzolan to split tensile strength of RCC mixture supports the data from this study.

The mixtures with fly ash has higher split tensile strength than mixtures with natural pozzolan in later ages.

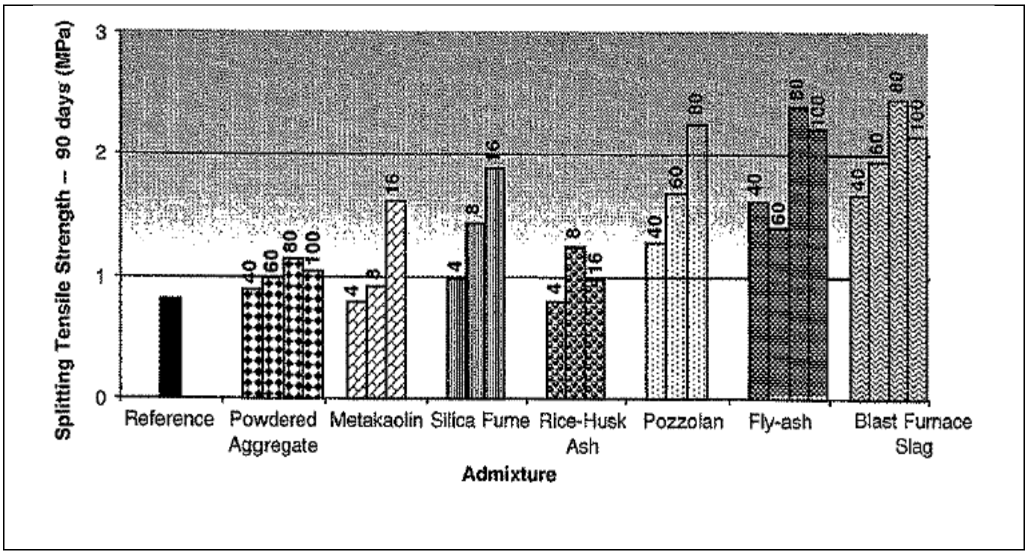


Figure 3-27 Split tensile strength of RCC [8]

A general summary of the split tensile strengths obtained v.s. cementitious material content are presented in Figure 3-28 for a range of projects around the world. Results from [30, 140, 141, 39, 51, 58, 21, 28, 142, 143, 144, 145, 41, 146, 53, 139, 57, 26, 40, 68] show that the split tensile strength is directly affected by the cementitious content as expected. However, the large variance in the obtained tensile strength for a chosen cement content (in different projects) is also evident. El Zapotillo Dam [139] presents a clear outlier on the data: very high cementitious content did lead to only a meager tensile strength. A similar strength could be obtained for the Nordlingaalda Dam using only 100kg of cementitious material. For the Ralco and Three Gorges Dams, strength values in excess of 2.5 MPa was obtained using a cementitious content of 150-200kg per cubic meter of RCC. The table of data is shown in Appendix B Table B.8.

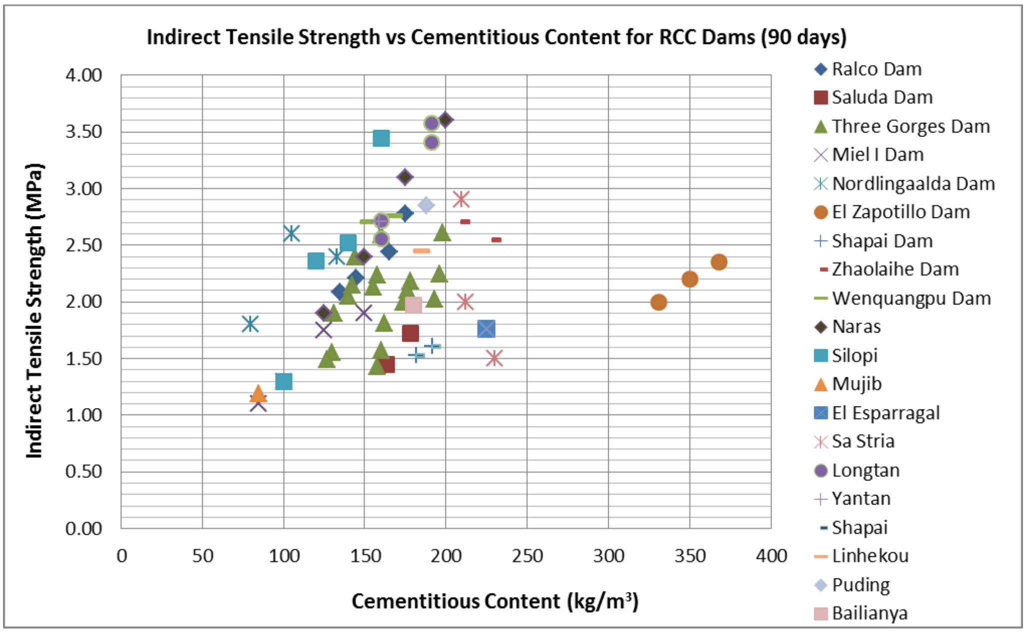


Figure 3-28 Indirect Tensile Strength vs Cementitious Content for RCC Dams

3.3.2.2 Tensile Strength to Compressive Strength

Correlation of the tensile strength to compressive strength is an important relation for RCC for practical reasons as the compressive strength of control cylinders or extracted cores from dams usually used for quality control during construction [28].

The split tensile strength of RCC mixtures are usually 5-15% of the compressive strength. The split tensile strength of mixtures with higher cementitious material contents and higher compressive strengths is typically a lower percentage of the compressive strength compared to mixes with lower cementitious content. Some examples of the ratio of split tension to compressive strength for various mixes at different projects according to collected data are 6.4 to 10% for Three Gorges, 10 to 12% for Miel I, 7.7 to 12% for Nordlingaalda, 14% for Mujib, 10% for

El Esparragal, 13.8 to 14.3% for El Zapotillo, 8.8% for Shapai, and 9.3 to 10% for Zhaolaihe. The indirect tensile strength of various mixes are compared to the compressive strength of the material in Figure 3-29 for some RCC dams for 90 days old specimens. The table of data is given in Appendix B Table B.9.

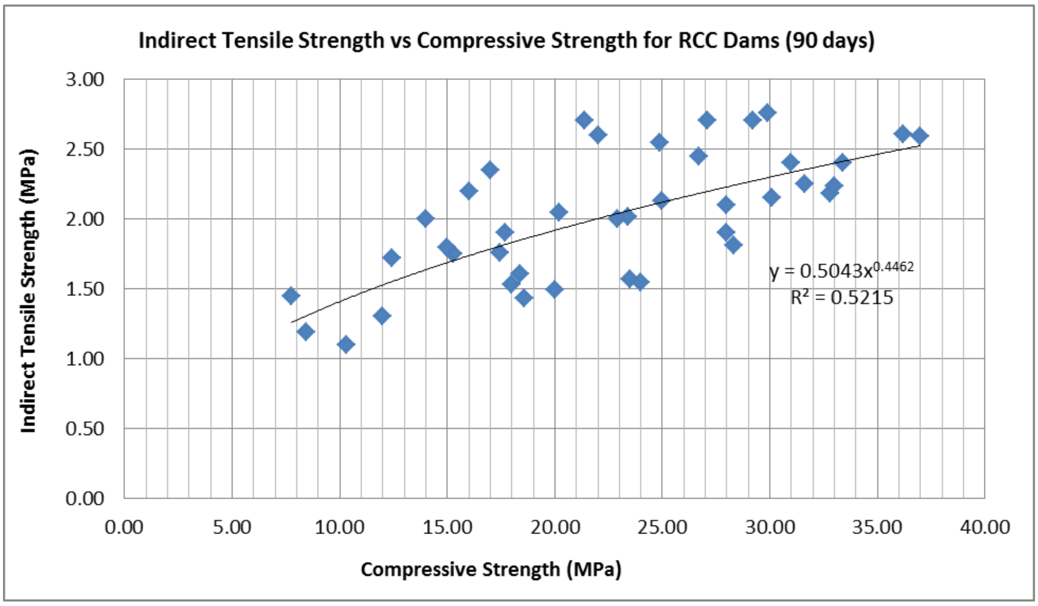


Figure 3-29 Indirect Tensile Strength vs Compressive Strength for RCC Dams

The best fit to the data yields the split tensile strength $f_{t,s}$ as a radical function of the compressive strength f_c as given in (3.1). The split tensile strength and the square root of compressive strength was also shown to be correlated well in Amer, Storey and Delatte [18]. The ratio between $f_{t,s}$ and f_c was given to be between 0.08 and 0.14, similar to CVC, in [4]. The split tensile strength values from all mixes fall in the range of 12-15 % of the compressive strength in Saluda RCC Dam as given in [30].

$$f_{t,s} = 0.5\sqrt{f_c} \tag{3.1}$$

The correlation between direct tensile strength and the compressive strength is also studied. As given in section 3.3.2, direct tensile strength is usually on the order of 65-75% of the split tensile strength. The relation between the direct and split tensile strengths is further quantified in Schrader [2] as given in (2), with the factor relating the split and direct tensile strengths expressed in terms of compressive strength f_c expressed in metric units of mega-pascals. This relation implies a higher direct tensile strength compared to the split tensile strength with an increasing compressive strength of the RCC material [23] [24].

$$f_{t,d} = 0.3 \log 10 f_c * f_{t,s} \tag{3.2}$$

Li, Zhang F., Zhang W. and Yang [25] conducted a direct tensile test on core specimens extracted from a practical RCC dam. The results showed that the direct tensile strength of RCC material is a function of the square root of its nominal compressive strength similar to the correlation for the split tensile strength. Similarly, Malkawi and Mutasher [27] built a test setup to predict the correlation between the direct tensile strength and the compressive strength of RCC. The direct tensile strength was obtained to be about 7 to 9% of the compressive strength.

As outlined above, the correlation and the relation obtained between the split/direct tensile strength and the compressive strength of the material can vary slightly for individual projects. A sound relation to use appears to be obtaining the tensile strength of the material as a linear function of the square root of its compressive strength as given in (3.1) or (3.2). The results from various projects show that the direct tensile strength should be between 5-10% of the compressive strength.

3.3.2.3 Tensile Strength of RCC Lift Joints

Tensile strength of the lift joints, formed during the sequential laying and compression of RCC lifts, is usually the critical parameter determining the strength of the RCC material. Tensile strength of lift joints are considerably less than the parent RCC due to bonding issues between sequential lifts. The tensile strength in the lift joints in the direction normal to the joint surface is critical near the upstream face of the dam as the direction of the principal tensile stress near the upstream face is very nearly normal to the joint surface. For the downstream face, the direction of the principal stress is almost parallel to the face: the parent concrete material at the maximum stress orientation has higher tensile strength compared to that of the lift joint. However, various factors can affect this relation,thus, it is necessary to study whether the principal stress or the tensile stress normal to the lift joint is higher to determine critical tensile stress [19].

The lift joint tensile strength is affected by the cementitious content of the mix, the cleaning and curing of the joint surface, the use of a bedding mix, the time elapsed between placing of consecutive horizontal lifts (lift maturity) and the size and grading of the aggregate [32] [34] [3]. Besides these, the workability of the mixture has good effect on the lift joint tensile strength due to increased density of the next layer with the depth and becoming maximum at the surface of bottom lift [63]. The core tests from Elk Creek and Willow Creek Dams showed the importance of workable concrete. [65]. However, the selection of thick lift depth decreases the compaction efficiency and accordingly density at the bottom of lift so that the lift joint tensile strength drops at this situation. Moreover, the contribution of bedding mix to lift joint tensile strength may not be seen if the mixture with workable high cementitious content is chosen [28].

The statistical methods can be applied to determine the design lift joint strength with the selected mixtures based on the probability of achieving joint strength with parameters of construction type and whether application of bedding mortar or concrete to the surface. The lift joint tensile strength is calculated based on workability, aggregate type and size and lift joint preparation. Low-strength aggregate and unbedded lift joints results in low lift joint direct tensile strength while crushed aggregates and bedded lifts does the opposite. The 5% of the compressive strength or 70% of the tensile strength of parent concrete can be assumed as the lift joint tensile strength when a detailed cast specimen or core testing is missed. The tensile strength of parent concrete is equivalent to the direct tensile strength or maximum of 75% of splitting tensile strengths [3] [4] [19].

Schrader [24] and Saucier [61] state that the lift joint tensile strength increases with increase in cementitious content of RCC mixture while Li, Zhang F., Zhang W. and Yang [25], point out to the importance of the size of aggregates in determining the lift joint strength as in [3]. They state that the RCC interface is not related to the square root of its nominal compressive strength but the maximum size of aggregate to the characteristic dimension of the specimen. Similarly, the larger aggregate causes surface roughness and leading voids in mixture so that use of it decreases the lift joint strength if the bedding mix of mortar or concrete is not used [64].

Lift joint tensile strength was shown to decrease gradually with increasing exposure time of lower lift in Ribeiro, Cascon and Gonçalves [33]. The lower lift must be cured well before the next lift is placed. In order to minimize the loss in the tensile strength, the next lift should be placed before the initial setting time of the previos lift however, under the conditions of rapid surface drying, it is necessary to cover the lift for two to three hours until the concrete attained initial set [62].

The effects of poor bonding in the lift joints were seen in the Platanovryssi Dam, due to insufficient curing and very hot weather, a significant reduction in the lift joint tensile strength was observed and the placement was forced to be stopped [24].

3.3.3 Modulus of Elasticity

The modulus of elasticity "E" is defined as the ratio of the normal stress to its corresponding strain for compressive and tensile stresses below the proportional elastic limit of the material. The modulus of elasticity is an important input parameter for the stress analysis of RCC dams. Modulus of elasticity significantly affects the fundamental properties for a dynamic analyses as well as changing the strain demand for thermal analyses.

There are various factors that affect the modulus of elasticity of RCC such as age, W/C ratio, aggregate type and cementitous material content. The modulus increases with age up to maximum value that correspond to the maximum that could be reached by the mortar or the aggregate (which is lesser). A high water to cement ratio results in low modulus of elasticity [3]. Aggregate type is another factor that influences the modulus: aggregates such as quartzite and argillite produce high modulus values, whereas, sandstone or similar aggregates reduce the value of elastic modulus. Properly proportioned RCC should have a modulus equal or greater than that of CMC of equal compressive strength [6]. Lean mixes have lower moduli, in some cases, lean RCC mixtures are used to obtain low modulus, because, low modulus tends to decrease the potential for cracking [58].

The modulus of elasticity is usually determined according to ASTM C 469 (CRD-C 19) "Standard Test Method For Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," or CRD-C 166, "Standard Test Method for Static Modulus of Elasticity in Tension," which are both procedures for a chord modulus [3]. The alternative methods for determining the modulus of elasticity use secant or tangent stiffness from the force-displacement curve. The differences between the methods are usually small. Test ages of 1,3,7,28,90,180 and 365 days may be considered for the determination of modulus.

American Concrete Institute (ACI) formulas for the determination of elastic modulus are not based on mass concrete mixtures and generally does not estimate mass concrete elastic modulus. For planning purposes only, $E = 2000 \sqrt{f_c}$ can be used as an estimate with the compressive strength f_c and E expressed in MPa and GPa, respectively. Many RCC tests indicated elastic modulus values higher than the ACI formula predicts.

Figure 3-30 shows the modulus of elasticity values of RCC dams for 7, 28, 90, 180 and 365 days. The table of data is given in Appendix B Table B.11. Figure 3-31 shows the modulus of elasticity vs. compressive strength plot for 90 days from the collected data of some RCC dams which correlates with the ACI formula given above.

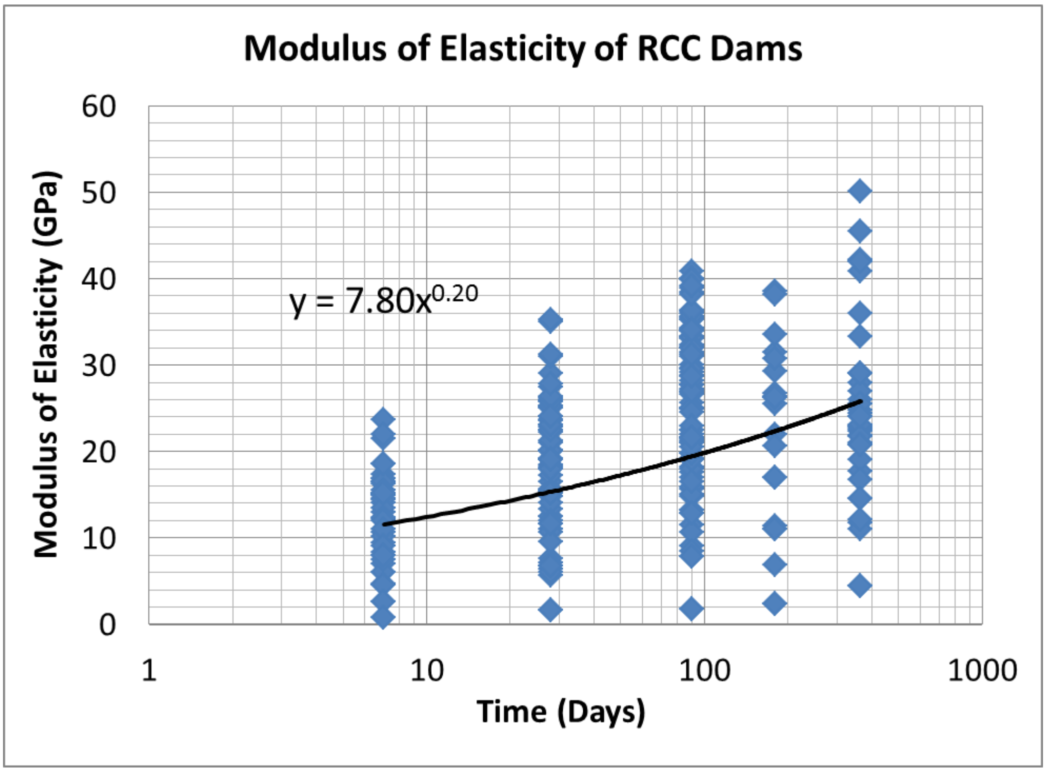


Figure 3-30 Modulus of elasticity values of RCC Dams

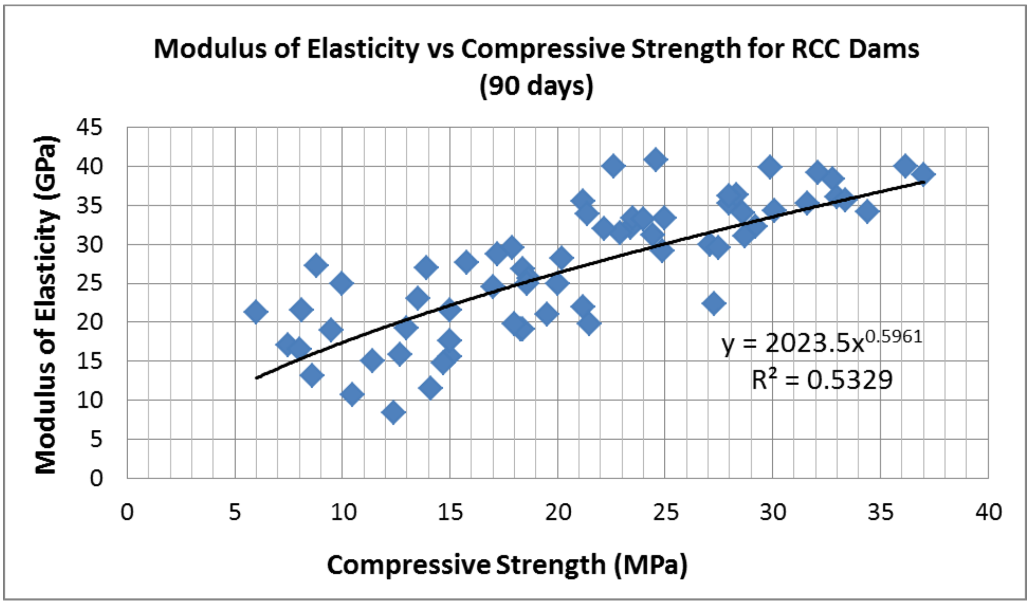


Figure 3-31 Modulus of elasticity vs. compressive strength for RCC Dams

3.3.4 Thermal Expansion Coefficient

The coefficient of thermal expansion is defined as the change in the linear dimension per unit length divided by the temperature change. For RCC, it is slightly higher than the thermal expansion coefficient of the aggregate and slightly less than that for the conventional concrete made with the same aggregate but more cement paste.

Extensive range of aggregates used in RCC mixtures lead to a wide range of the coefficient of thermal expansion for RCC. For this reason testing with the full mixture is recommended. Typically, the coefficient of thermal expansion for RCC varies between 7 and 14 millionths per degree Celcius. A value of 9 millionths per Celcius can be used for preliminary RCC design works [2]. The table of data is given in Appendix B Table B.10.

3.3.5 Creep

Creep is the time dependent deformation of concrete due to sustained load. Creep starts just after the load is applied and continues at a decreasing rate as long as the load remains. Creep is affected by the aggregate and concrete modulus of elasticity and compressive strength of the concrete. Concrete with high aggregate and concrete modulus of elasticity generally has low creep property. For mass concrete, the ability to dissipate thermal stress is proportional to the relief of the sustained stress. Mixtures with high cementitious content have a more solid cementing matrix and lower creep so they tend to produce higher thermal stress. Thus, higher creep properties are desired to relieve thermally induced stress and strains in mass concrete structures [6].

Creep of the concrete is measured according to ASTM C 512, "Standard Test Method For Creep of Concrete in Compression." Sealed specimens are used in tests to avoid drying shrinkage effects. The method suggests five ages of loading between 2 days and a year to determine creep behaviour appropriately. Creep is represented by the following formula. The first part, $(\frac{1}{E})$, represents the initial elastic strain loading, and the second part represents the long term effects of creep after loading:

$$\varepsilon = \frac{1}{E} + F\ K\ \ln(t+1) \qquad (3.3)$$

Where ε represents the specific creep, or total strain per stress, E the static modulus of elasticity, $F(K)$ the rate of creep and, t the time elapsed after loading in days. $F\ K$ values for RCC have ranged from 1.5 to 29 millionths per MPa with the higher numbers corresponding to lower compressive strength mixtures [3].

3.3.6 Durability

3.3.6.1 Freeze and Thaw Resistance

The freeze-thaw resistance of the RCC mixture directly depends on its strength, impermeability and air entrainment capability. Cementitious content without pozzolan is adviced for RCC surfaces where the surface is exposed to early freeze-thaw cycles while wet since high early strength is needed under these cases [6][50][41]. According to Zhengbin, Jinrong and Xiaoyan [20], in order to increase the freeze-thaw durability of RCC mixtures, air entrained admixtures content should be increased, air containing should be controlled at 4.5 – 6.0 %, fly ash content should be no more than 40 % to high air-containing concrete and the water-colloid ratio of RCC should be under 0.55 in cold regions. Furthermore, the capillary water transport in RCC increase the vulnerability of mixture to take damage from freeze-thaw cycles. This action occurs more common in leaner mixtures which infiltrate water inside easier. [60]

Since RCC mixture has dry consistency, it is not practical to entrain air in mixture. Laboratory specimens of non air entrained RCC mixtures are tested according to ASTM "Test Method for Resistance of Concrete to Rapid Freezing and Thawing" (C 666). Test results show that non air entrained RCC mixtures behave poorly against freeze-thaw cycles. On the other hand, laboratory specimens with air entraining admixtures demonstrates good freeze-thaw durability. Air entrainment was incorporated in RCC mixtures for Zintel Canyon, Nickajack, Santa Cruz and Lake Robertson Dams and others [1].

Nonetheless, there are various examples of great freeze-thaw resistance of non air entrained RCC in the construction field. According to Schrader [2], Winchester, Willow Creek, Monksville and Middle Ford Dams which have unformed and uncompacted downstream face exposed to almost daily freeze-thaw cycles during winters, but, all of these dams exhibited good freeze-thaw durability.

3.3.6.2 Abrasion and Erosion Resistance

The abrasion-erosion resistance of RCC is highly dependent on RCC compressive strength and grading, quality and the maximum size of the aggregate. Erosion tests show good erosion resistance behaviour for RCC. It is determined that abrasion resistance of RCC increases with increasing compressive strength and maximum aggregate size. Some RCC dam overflow spillways are made with RCC and show good resistance against high velocity and discharges. Abrasion-erosion resistance performance of RCC have been studied on many projects. Salto Caxias Dam, the spillway rehabilitation of Tarbela Dam, the spillway of the North Folk of the Toutle River Dam, Kerrville Ponding Dam and Detroit Dam have shown good abrasion-erosion resistance [6].

According to tests done by U.S. Army Corps of Engineers (1981), cavitation and erosion rates for RCC spillway surfaces are developed. Test results show that an erosion rate of 0.002 lb/ft^2/hr for rolled surface and 0.05 lb/ft^2/hr for rough surface have been obtained and confirmed as reasonable. On the other hand, the spillways at both Willow Creek and Galesville Dams have exposed RCC flow surfaces. The spillway surfaces may not constructed with conventional concrete line based on cost and infrequent use,but, at Galesville Dam in 1996 and 1997 flooding resulted in a irregular hydraulic flow surface that jumped off the spillway face in some locations. Therefore, comprehensive laboratory test for the spillway surfaces that can be prone to high velocity flows across spillway should be conducted. Spillways subjected to frequent high velocity flows are still faced with conventional concrete [4].

ASTM Test Method for Abrasion Resistance of Concrete is used to evaluate abrasion performance of RCC.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

In this study, first, the seismic and thermal analyses of RCC dams were investigated. Useful information from seismic and thermal performance of existing dams was compiled in order to determine recommendations for the evaluation of such systems. The following conclusions were drawn from the first part of the study:

- The method of analysis directly affects the results of seismic and thermal analyses. This selection should be done by considering the size and geometry of dam, geological and environmental conditions of the site and the purpose of the analysis.

- Dam-reservoir-foundation interaction should be taken into account when analyzing the seismic response of a RCC dam. Reservoir hydrodynamic load effect, reservoir bottom absorption and viscous damping combined with foundation radiation affect the seismic demand significantly.

- The principal tensile stresses are directly related with elastic modulus of foundation. As the ratio of modulus of elasticity of concrete to modulus of elasticity of foundation increases, the principal stresses decrease.

Soft foundation leads lower stresses on the dam body while increasing the deformation capacity of dam.

- Slope discontinuity especially at the heel and neck causes stress concentration at these locations so that the upstream and downstream slopes should be kept constant if the design permits. Reinforcement bars can be placed at the stress concentration location which reduces crack propagation resisting against sliding in the cracked region.

- The cementitious material content, concrete placement temperature and the starting season of placement are the most important factors for affecting thermal cracking on RCC dams. Concrete placement in hot seasons should be avoided.

- Aggregate pre-cooling, use of ice or chilly water and surface insulation using geomembranes are the key precautions to prevent thermal cracks.

The mixture content, mixture design, proportioning and material properties of RCC were studied in the second part of this work. The factors affecting these attributes were underlined. The proper material selection criterias for mixture design were addressed. The effect of types of pozzolans and aggregates on mixture design and strength gain was presented. The material property and mixture content data such as compressive strength, cementitious content, W/C ratio etc. were surveyed from the literature. The conclusions of these studies can be summarized as followings:

- The use of fly ash in RCC mixtures leads to long term strength contribution and reduction of heat of hydration which is very important for thermal issues. Percentages around 30~40% generally seem to be ideal for obtaining the optimum compressive strength with respect to the volume of the material used.

- The aggregates having characteristics of good gradation, high quality, crushed, angular shapes influence the strength development in a positive manner. Moreover, the use of fine particles reduce the need for the use of water by filling the voids in mixture thus improving the strength.

- The strength of concrete increases as the W/C ratio of mixture decreases. It also increases with the increase of cementitious content in a mixture but is exposed to a reduction of strength efficiency.

- Aggregate type directly affects the modulus of elasticity of mixture. Aggregates such as quartzite and argillite produce high modulus while sandstone and similar types reduce the value of elastic modulus.

- The mixtures with low or no pozzolan should be chosen for the protection of RCC surfaces against freeze-thaw cycles since high early strength is needed.

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APPENDIX A

TABLES OF RCC DAMS, MIX CONTENT AND DESIGN

Table A.1 General Description of RCC Dams

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions Height (m)	Dimensions Length (m)	Volume RCC (m^3x10^3)	Volume Total (m^3x10^3)	Facings Upstream Slope	Facings Downstream Slope
Beni Haroun	Algeria	IW	El Kebir	963	118	714	1690	1900	V	0.8
Koudiat Acerdoune	Algeria	IW	Wadi Isser	800	121	500	1650	1850	0.65	0.65
Boussiaba	Algeria		Boussiaba	120	51	310	160	190	V	
Capanda	Angola	H	Kwanza	4795	110	1203	757	1154	V	0.7
Urugua-i	Argentina	H	Urugua-i	1175	77	687	590	626	V	0.8
Copperfield	Australia	W	Copperfield	20	40	340	140	156	V	V & 0.9
Craigbourne	Australia	IW	Coal	13	25	247	22	24	V	1
Wright's Basin	Australia	F	Point Hut Creek	1	18	86	9	9	V	1
New Victoria	Australia	W	Munday Brook	10	52	285	121	135	V	0.325 & 0.8
Kroombit	Australia	GI	Kroombit Creek	13	26	250	84	110	V	0.7
Burton Gorge	Australia	W	Isaac	20	26	285	64	68	V & 1	0.8 & 1
Lower Molonglo Bypass	Australia	P	Unnamed creek	1	32	120	22	27	V	0.8
Loyalty Road flood retarding	Australia	F	Darling Mills Creek	-	30	111	20	22	V	0.8
Cadiangullong	Australia	W	Cadiangullong Creek	4	43	356	114	123	V	0.75
Paradise (Burnett River)	Australia	FI	Burnett	300	50	940	400	400	V	
Meander	Australia	IW	Meander	43	47	180	85	85	V	0.7
North Para	Australia	F	North Para		33	206	50	50	V	
Wyaralong	Australia	W	Teviot Brook	1	48	464	173	0		
Enlarged Cotter	Australia	W	Cotter	78	82	350	0	400	V	0.75
Chalillo	Belize	H	Macal		45	380	140	0		
La Cañada	Bolivia	I	Comarapa	10	52	154	72	77	V	0.22 & 0.75
Saco de Nova Olinda	Brazil	FIW	Gravata	95	56	230	132	143	V	0.8

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions Height (m)	Dimensions Length (m)	Volume RCC (m^3x10^3)	Volume Total (m^3x10^3)	Facings Upstream Slope	Facings Downstream Slope
Caraibas	Brazil	FI	Caraibas	10	26	160	18	22	0.1	0.8
Gameleira	Brazil	FIRW	Gameleira	2	29	150	27	29	V	
Pelo Sinal	Brazil	W	Taperobá	76	34	296	69	80		
Acauã	Brazil	FIW	Paraíba	247	46	375	674	0		
Varzea Grande	Brazil	W	Picuí	21	31	135	27	28		
Cova da Mandioca	Brazil	I	Cova da Mandioca	126	32	360	71	75	V	0.75
Trairas	Brazil	W	Seridó	49	25	440	27	28		
Canoas	Brazil	W	Saõ Gonçalo	69	51	116	87	93	0.1	0.8
Jordão	Brazil	H	Jordão	110	95	550	570	647	V	0.74
Belo Jardim	Brazil	IW	Ipojuca	37	43	420	81	93		
Rio do Peixe	Brazil	H	Do Peixe	2	20	300	20	34	V	0.8
Salto Caxias	Brazil	H	Iguaçu	3600	67	1083	912	1438	V	0.75
Val de Serra	Brazil	W	Ibicui-Mirim	24	37	675	69	95	V	
Jucazinho	Brazil	FIRW	Capiibaribe	286	63	442	472	500	V	0.75
Guilman- Amorin	Brazil	H	Piracicaba	12	41	143	23	72		
Bertarello	Brazil	W	Arroio Burati	6	29	210	60	70	V	
Rosal	Brazil	H	Itabapoana		37	212	45	75		
Ponto Novo	Brazil	W	Itapicuru-açu	39	32	266	90	105		
Santa Cruz do Apodi	Brazil	FIRW	Apodi	600	58	1660	1070	0		
Tucuruí - 2nd Phase	Brazil	H	Tocantins		78	1541	76	8800		
Dona Francisca	Brazil	H	Jacuí	335	63	670	485	665		
Umari	Brazil	FIRW	do Carmo	293	42	2308	644	658		
Pedras Altas	Brazil	FIRW			24	1090	172	192		
Pirapana	Brazil	W			42	300	87	137		
Cana Brava	Brazil	H	Tocantins		71	510	400	620		
Castanhão	Brazil	FIRW	Congonhas	800	60	668	890	1030		

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Lajeado	Brazil	H	Tocantins		34	2100	210	1330		
Serra do Facão	Brazil	H			80	326	600	700		
João Leite	Brazil	H	João Leite	129	55	380	270	290		
Fundão	Brazil	H			49	445	180	210		
Candonga	Brazil	H			53	311	236	356		
Pindobaçu	Brazil	H			44	210	75	85		
Bandeira de Malo	Brazil	H			20	320	75	87		
Santa Clara - Jordão	Brazil	H	Jordão	431	67	588	438	504		
Estreito	Brazil	FIRW	Tocantins		69	540	0	0		
Lac Robertson	Canada	H	Ha! Ha!	587	40	124	28	35	V	0.75
Grand Falls spillway	Canada	H	Exploits	-	15	180	7	11	V	0.67
Pangue	Chile	H	Bio-Bio	175	113	410	670	740	V	0.8
Ralco	Chile	H	Bio-Bio	1200	155	360	1596	1640	V	0.8
Kengkou	China	HW	Youxi	27	57	123	43	62	V	0.75
Rongdi	China	FHI	Dulanghe	19	53	136	61	74	V	0.75
Longmentan Nº1	China	HIW	Dazhangxi	53	58	150	71	93	V&0.3	0.75
Tongjiezi (with Niurixigou	China	FHIN	Daduhe	200	88	284	407	855	V	0.75
Tianshenqiao Nº2	China	FH	Nanpanjiang	116	61	470	143	284	V	V&0.40
Yantan	China	FHN	Hongshuihe	3380	110	525	626	905	V	V&0.80
Shuikou	China	FHI	Mingjiang	2340	101	791	600	1710	V	0.73
Wan'an	China	FHIN	Gangjiang	2216	68	1104	156	1480	V	0.8
Guangzhou PSS - Lower dam	China	H	Liuxihe	28	44	127	32	57	V	0.7
Suoshai	China	H	Sancha	420	75	196	0	88		
Jinjiang	China	FH	Jinjianghe	189	68	229	182	267	V	0.75
Puding	China	HIW	Sanchahe	920	75	196	103	145	V	0.35
Shuidong	China	HN	Youxi	108	63	197	126	184	V	0.75
Daguangba	China	HIW	Changhuajiang	1710	57	827	485	857	V	0.75

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Shanzai	China	FHIW	Aojiang	167	66	274	180	272	V	0.8
Wenquanpu	China	FHIW	Tanghe	7	48	188	55	63	V	0.3
Xibingxi	China	HW	Longshanxi	9	64	93	25	33	V&0.08	0.65
Guanyinge (Kwan-in-Temple)	China	FHIW	Taizihe	2168	82	1040	1240	1815	V&0.1	0.7
Shimantan	China	FIW	Gunhe	120	40	675	272	351	V	0.75
Bailongtan	China	HIN	Hongshuihe	340	34	247	62	80	V	0.7
Mantaicheng	China	HI	Gayahe	10	37	337	78	100	V	0.75
Wanyao	China	FHIW	Dahexi	223	83	390	320	458	V&0.2	0.7
Shuangxi	China	FHIW	Meixihe	91	52	221	113	172	V	0.8
Shibanshui	China	HR	Longxihe	105	85	445	335	564	V	0.65
Taolinkou	China	FHIRW	Qinglonghe	859	75	501	585	1350	V&0.15	0.78
Yongxi N°3	China	FHW	Dazhangxi	68	87	198	170	255	V	0.73
Huatan	China	H	Yunhe	82	85	173	240	290	0.2	0.8
Changshun	China	HW	Yujiang	68	69	279	170	200	V	0.74
Fenhe N°2	China	FHW	Fenhe	130	87	350	362	448	V&0.20	0.75
Jiangya	China	FHINW	Loushui	1741	131	370	1100	1386	V	0.8
Songyue (1st Stage)	China	FHIRW	Hailanhe	21	31	271	44	77	V	0.73
Baishi	China	FHIW	Dalinghe	1645	50	523	111	503	V&0.10	0.7
Hongpo	China	W	Qinggoushui	3	55	244	71	77	V	0.5
Gaobazhou	China	FHN	Qingjiang	536	57	440	210	940	V	0.75
Yanwangbizi	China	FHIW	Dalinghe	217	35	383	87	224		
Yushi	China	FIW	Biliuhe	89	50	267	0	233		
Shankou N°3	China	FH	Du’anshui (Chengjiang)	48	57	179	90	119	V	0.75
Shapai	China	H	Caopohe	18	132	250	365	392	V&-0.10	0.21
Shimenzi	China	HIW	Taxihe	80	109	176	188	211	V&0.142	V&0.18
Longshou N°1	China	H	Heihe	13	80	258	187	210	V&0.20	0.75

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height	Length	RCC	Total	Upstream	Downstream
					(m)	(m)	(m^3x10^3)	(m^3x10^3)	Slope	Slope
Dachaoshan	China	FH	Lancangjiang	111	111	460	757	1287	V&0.20	0.7
Mianhuatan	China	FHNW	Dingjiang	940	113	302	500	615	V	0.75
Helong	China	HRW	Hailanhe	30	30	244	43	89	V	0.75
Xiao Yangxi (and saddle dam)	China	W	Xiaoyangxi	15	45	118	47	49	V	0.75
Wanmipo	China	HN	Youshui	378	65	238	141	375	V	0.75
Linhekou	China	HI	Lanhe	147	100	311	229	293	curve	curve
Zhouning	China	H	Muyangxi	47	73	206	159	199	V	0.72
Zhaolaihe	China	H	Duhe	70	107	206	166	254	curve	curve
Xihe	China	FHN	Hanjiang	229	62	346	194	631		
Suofengying	China	FHINW	Kido/Liuguanghe	18	122	165	421	739	V&0.25	0.7
Zaoshi	China	FHNW	Xieshui	1440	88	351	450	930	V&0.25	0.8
Baisha	China	FH	Wan'anxi	199	75	172	211	239		
Zhouba	China	FH	Mabianhe	202	73	172	229	405	V	0.7
Tukahe	China	H	Lixiangjiang	78	59	300	255	570	V	
Baise	China	FHINW	Yojiang	5660	130	734	1995	2672	V	0.8
Dahuashui	China	H	Qingshuihe	277	135	306	550	650	curve	curve
Bailianya	China	FHIW	Manshuihe	453	104	348	485	560	V	0.335
Huizhou PSS - Upper Dam	China	H	Xiaojinhe	32	57	168	84	93	V	0.75
Jing Hong	China	FHR	Lancanjiang	1139	108	433	848	1140	V	0.8
Pengshui	China	H	Chongqing	409	117	326	608	1330	V	0.7
Huanghuazhai	China	H	Getu	1748	110	275	280	0		
Longtan	China	FHNW	Hongshuihe	27270	217	849	4952	7458	V&0.25	0.7
Guangzhao	China	H	Beipanjiang	3245	201	412	820	2870	V&0.25	0.75
Gelantan	China	H	Lixianjiang	409	120	466	903	1200	V&0.20	0.75
Silin	China	FHIN	Wujiang	1593	117	316	825	1100	V	0.7
Jin’anqiao	China	HNR	Jinishajiang	847	156	640	2400	3920	V	0.75

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions Height (m)	Dimensions Length (m)	Volume RCC (m^3x10^3)	Volume Total (m^3x10^3)	Facings Upstream Slope	Facings Downstream Slope
Longkaikou	China	FHNRW	Jinshajiang	657	119	768	2840	3853	V	0.75
Wudu	China	FHIW	Fu	594	123	637	1151	1580	V	0.75
Porce II	Colombia	H	Porce	211	123	425	1305	1445	0.1	0.35&0.50
Miel I	Colombia	H	La Miel	565	188	345	1669	1730	V	0.75&1.00
Peñas Blancas	Costa Rica	H	Peñas Blancas	2	48	211	120	170	V	0.80
Pirris	Costa Rica	H	Pirris	36	113	265	695	755	0.33	0.50
Contraembalse de Monción	Dominican Republic	FHI	Mao	8	20	254	130	155	0.70	0.67
Panalito	Dominican Republic	H	Tireo	4	52	210	73	100		
Toker	Eritrea	W	Toker	14	73	263	187	210	V	0.80
Gibe III	Ethiopia	H	Omo	14690	246	610	0	5700		
Les Olivettes	France	F	La Peyne	4	36	255	80	85	V	0.75
Riou	France	HIR	Riou	1	26	308	41	46	V	0.6
Choldocogagna	France	W	Lessarte	1	36	100	19	23	0.10	0.75
Villaunur	France	F	Le Cantache	7	16	147	11	15	V	0.75
Sep	France	I	Sep	5	46	145	49	58	V	0.72
La Touche Poupard	France	I	Chambon	15	36	200	34	46	V	0.75
Petit Saut	French Guyana	H	Sinnamary	3500	48	740	250	410	V	V&0.80
Marathia	Greece	IW	Marathia	3	28	265	31	48	0.5	0.5
Ano Mera	Greece	IW	Ano Mera	1	32	170	49	64	0.5	0.5
Platanovryssi	Greece	HI	Nestos	84	95	305	420	440	0.1	0.75
Steno	Greece	IW	Steno	1	32	170	69	70	0.7	0.7
Lithaios	Greece	I	Lithaios		32	526	160	220	0.8	0.8
Koris Yefiri (Maiden's Bridge)	Greece	IW	Partheni	3	42	221	170	190	0.8	0.8
Valsamiotis	Greece	I	Valsamiotis		65	330	640	820	0.8	0.8
Concepción	Honduras	W	Concepción	35	68	694	270	290	0.075	0.8
Nacaome	Honduras	W	Rio Grande Nacaome	42	54	320	250	300	0.15	0.8

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height	Length	RCC	Total	Upstream	Downstream
					(m)	(m)	(m^3x10^3)	(m^3x10^3)	Slope	Slope
Nordlingaalda	Iceland	H	Upper-Thjorsa		21	285				
Ghatghar (Upper dam)	India	H	Pravara	6	15	503	35	40	V	0.78
Ghatghar (Lower dam)	India	H	Shahi Nallah	3	86	447	638	646	0.141	0.782
Krishna Weir (Srisailam)	India	H	Krishna		40	305	42	72		
Middle Vaitarna	India	W	Vaitarna	202	103	550	1200	1400	0.15	0.75
Balambano	Indonesia	H	Larona	31	95	351	528	534	V	0.80
Pie Pol	Iran	FH	Karkeh	29	15	300	130	270		
Jahgin	Iran	FIW	Jahgin	300	78	220	232	382	V&0.30	0.75
Zirdan	Iran	IW	Kajoo	207	65	350	265	465	0.90	1.20
Javeh	Iran	FI	Javeh Roud	175	95	330	700	816		
Badovli	Iran	I	Ag-Su	34.73	99	234	350	410	V&0.33	0.85
Sa Stria	Italy	I	Monte Nieddu		84	345	500	500		
Shimajigawa	Japan	FIW	Shimaji	21	89	240	165	317	V&0.30	0.8
Tamagawa	Japan	FHIW	Tama	254	100	441	772	1150	V&0.60	0.81
Mano	Japan	FHW	Mano	36	69	239	104	219	V	0.8
Shiromizugawa	Japan	FI	Shiromizu	5	55	367	142	314	V	0.8
Asahi Ogawa	Japan	FH	Ogawa	5	84	260	268	361	V&0.90	0.8
Nunome	Japan	FW	Nunome	17	72	322	110	330	V&0.40	0.76
Pirika	Japan	FHI	Shirobeshit-oshibetsu	18	40	755	163	360	V&0.80	0.8
Dodairagawa	Japan	FW	Kabura	5	70	300	167	350	V&0.40	0.75
Asari	Japan	FW	Asari	9	74	390	259	517	V&0.30	0.8
Kamuro	Japan	FW	Kaneyama	7	61	257	136	307	V&0.60	0.75
Sakaigawa	Japan	FHIW	Sakai	60	115	298	373	718	V&0.80	0.78
Sabigawa (lower dam)	Japan	H	Kosabi	11	104	273	400	590	0.1	0.8
Ryumon	Japan	FIW	Sakoma	42	100	378	521	836	V&0.30	0.8
Tsugawa	Japan	FHW	Kamo	6	76	228	222	342	V&0.60	0.76

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Miyatoko	Japan	FW	Miyatoko	5	48	256	172	280	0.6	0.8
Kodama	Japan	FW	Kodama	14	102	280	358	570	V&0.20	0.76
Hinata	Japan	F	Kasshi	6	57	290	113	232	V	0.75
Miyagase	Japan	FHW	Nakatsu	19	156	400	1537	2060	0.2&0.60	0.625
Yoshida	Japan	FW	Yoshida	2	75	218	193	304	V	0.75
Chiya	Japan	FHW	Takahashi	28	98	259	396	670	V	0.77
Ohmatsukawa	Japan	FHW	Matsu	12	65	296	141	294	V&0.70	0.76
Satsunaigawa	Japan	FHIW	Satsunai	54	114	300	536	770	0.4	0.8
Shiokawa	Japan	FIW	Shio	12	79	225	299	388	0.1&0.70	0.76
Urayama	Japan	FHW	Urayama	58	156	372	1294	1750	V&0.65	0.8
Shimagawa	Japan	FW	Shima	9	90	330	390	516	V&0.50	0.8
Hiyoshi	Japan	FHW	Katsura	66	70	438	440	670	V&0.80	0.8
Tomisato	Japan	FIW	Dozan	53	111	250	409	510	V	0.76
Takisato	Japan	FHIW	Sorachi	108	50	445	327	455	0.06	0.8
Kazunogawa	Japan	H	Tuchimuro	12	105	264	428	622	V&0.10	0.82
Hayachine	Japan	FHIW	Hienuki	17	74	333	141	333	V&0.20	0.76
Gassan	Japan	FHIW	Bonji	65	123	393	731	1160	V	0.8
Kubusugawa	Japan	FHIW	Kubusu	10	95	253	364	469	V&0.40	0.78
Nagashima sediment dam	Japan		Ohi	1	33	127	23	55	1.20	1.20
Ohnagami	Japan	FIW	Sutu	19	72	334	284	362	V&0.25	0.79
Origawa	Japan	FN	Ori	15	114	331	673	742	V&0.60	0.77
Shinmiyagawa	Japan	I	Miya	10	69	325	393	480	V	0.83
Ueno	Japan	H	Jinryu	19	120	350	269	720	V&0.30	0.84
Chubetu	Japan	FHIW	Chubetu	93	86	290	523	1007	V&0.80	0.8
Fukuchiyama	Japan	FNPW	Fukuti	3	65	255	115	201	V	0.78
Kutani	Japan	FW	Daishoji	25	76	280	188	360	V&0.80	0.8
Koyama	Japan	FIW	Ohkita	17	65	462	270	531	V	0.78

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Takizawa	Japan	FNW	Nakatu	63	140	424	810	1670	0.15&0.70	0.72
Hattabara	Japan	FW	Ashida	60	85	325	228	500	V&0.20	0.75
Kido	Japan	FINW	Kido	19	94	350	291	501	V&0.10	0.78
Nagai	Japan	FNW	Okitamano	51	126	381	703	1200	V&0.50	0.73
Toppu	Japan	FIW	Toppu	36	78	309	280	530	V&0.80	0.8
Kasegawa	Japan	FINW	Kase	71	97	455	862	965	V&0.60	0.75
Yubari Syuparo	Japan	FHIW	Yubari	427	111	390	440	940	V&0.80	0.82
Tannur	Jordan	I	Wadi al Hasa	17	60	270	250	250	V&1.00	0.80
Wala	Jordan	G	Wala	9	52	300	240	260	0.3	0.70
Mujib	Jordan	IW	Mujib	35	67	490	654	694	0.1	0.80
Sama El-Serhan	Jordan	I			10	120				
Al Wehdah	Jordan/Syria	W	Yarmouk	110	103	485	1426	1478	V&0.60	0.80
Buchtarma	Kazakhstan	FH	Irtysh	31000	90	450	587	988	V	0.80
Tashkumyr	Kyrgyzstan	HI	Naryn	140	75	320	100	1300	V	0.78
Nakai, part of Nam Theun 2 HPP	Laos	H	Nam Theun	3530	39	436	155	200		
Nam Gnouang (Theum Hinboun Expansion)	Laos	H	Nam Gnouang		70	470	383	0	V	0.80
Kinta	Malaysia	W	Kinta	30	78	700	952	975	V	0.80
Batu Hampar	Malaysia	W	Batu Hampar	3	75	236	200	203		
Bengoh	Malaysia	W	Sungai Bengoh	144	63	267	130	172	V	0.80
La Manzanilla	Mexico	F	Ibarrilla	1	36	150	20	30	V&0.25	V&0.75
Trigomil	Mexico	I	Ayuguila	324	100	250	362	681	V&0.24	V&0.80
Vindramas	Mexico	FI	El Bledal	102	50	807	117	184	V	0.8
San Lazaro	Mexico	FGW	San Lazaro	11	38	176	35	53	V&0.20	0.8
San Rafael	Mexico	FH	Santiago	13	48	168	85	110	V	0,66&0.80
Las Blancas	Mexico	I	Álomo & Soso	124	28	2795	221	316	V	V&0.75
Rompepicos at Corral des Palmas	Mexico	F		100	109	250	380	400	V&0.25	V&0.75

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions Height (m)	Dimensions Length (m)	Volume RCC (m^3x10^3)	Volume Total (m^3x10^3)	Facings Upstream Slope	Facings Downstream Slope
Amata	Mexico	I	San Lorenzo	14	30	218	53	60	V	1
El Zapotillo	Mexico	W	Verde	910	132	271	1100	1200	V	0.83
Ain al Koreima	Morocco	I	Akreuch	1	26	124	17	20	0.2	0.2&0.75
Rouidat Amont (Rwedat)	Morocco	IW	Rwedat	3	24	125	25	27	0.4	0.4
Aoulouz	Morocco	FHI	O. Souss	110	79	480	680	830	V	0.85
Joumoua	Morocco	W	Joumoua	7	57	297	150	200	0.2	0.8
Imin el Kheng	Morocco	GI	Oueld Berhil	12	41	170	109	118	0.2	0.8
Sahla	Morocco	IW	Sahla	62	55	160	130	160	0.2	0.9
Enjil	Morocco	IW	Taghoucht	12	43	80	45	57	0.2	0.8
Bouhouda	Morocco	IW	Sraa	56	55	174	165	187	0.2	0.8
Bab Louta	Morocco	W	Bousebaa	37	55	110	63	77	V	0.75
Ahl Souss (Ait M'Zal)	Morocco	W	Izig	5	41	222	49	76	0.2	0.8
Hassan II (Sidi Said)	Morocco	FIW	Moulouya	400	122	577	590	690	V	0.6
Oued R'Mel	Morocco	FW	R'Mel	25	79	250	230	243	V	0.75
Sidi Yahya (Ain Kwachia)	Morocco	IW	Oued Khellata	11	25	213	60	65	0.2	0.8
Sehb el Merga	Morocco	FIW	Sehb el merga	7	40	480	70	92	V	0.8
El Maleh	Morocco	F	El Maleh	35	49	174	100	140	0.2	0.6
Ait Mouley Ahmed	Morocco	IW	Ain Leuh	2	29	136	18	20	V	0.8
Yeywa	Myanmar	H	Myitinge	2600	135	680	2473	2843	V	0.8
Upper Paung Laung	Myanmar	H	Paung Laung	1300	103	530	950	1100	V	0.8
Wadi Dayqah	Oman	W	Wadi Dayqah	100	75	410	590	650	V	0.75
Mangla Emergency Spillway Control Weir	Pakistan	IW	Jhelum	6500	17	370	54	79	V&0.30	V&0.70
Gomal Zam	Pakistan	FHI	Gomal	St.1:1065, St.2:1424	133	231	390	474	V	0.60
Changuinola 1	Panama	H	Changuinola	347	105	595	884	910	V&0.33	0.75
Capillucas	Peru	H	Canete	5	34	60	75	75	0.375	0.75
Pedrógão	Portugal	FHI	Guadiana	106	43	448	149	354	V	0.80
Vadeni	Romania	H	Jiu	5	25	55	14	17		

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Tirgu Jiu	Romania	H	Jiu	2	24	61	13	26		
Bureiskaya	Russia	FH	Bureya	21000	136	714	1200	3500	V	0.70
De Mist Kraal	South Africa	IW	Little Fish	4	30	300	35	65	V	0.6
Arabie	South Africa	IW	Olifants	104	36	455	101	142	V	0,5&0.75
Zaaihoek	South Africa	W	Slang	190	47	527	97	134	V	V&0.62
Knellpoort	South Africa	W	Rietspruit	137	50	200	45	59	V	0.6
Spitskop	South Africa	I	Harts	61	15	100	17	36	V	0.7
Wolwedans	South Africa	W	Great Brak	24	70	268	180	210	V	0.5
Wriggleswade	South Africa	W	Kubusie	94	34	737	134	165	V	V&0.62
Glen Melville	South Africa	W	Ecca	7	32	380	66	114	V	V&0.75
Thornlea	South Africa	I	Mlazi	3	17	135	16	17	V	0.9
Taung	South Africa	IW	Harts	66	50	320	132	153	V	V&0.75
Paxton	South Africa	I	Tsorwo	1	17	70	3	3	V&0.50	V&0.50
Qedusizi (Mount Pleasant)	South Africa	F	Klip	128	28	490	78	156	V	V&0.70
Inyaka	South Africa	W	Marite	123	53	350	160	327	V	0.68
Nandoni (formerly Mutoti)	South Africa	IW	Luvuvhu	164	47	392	150	316	V	0.75
Bramhoek	South Africa	H	Braamhoekspruit	27	37	330	90	98	V	0.67
De Hoop	South Africa	W	Steelpoort	347	85	1015	880	950	V	
Castilblanco de los Arroyos	Spain	W	Cala	1	25	124	14	20	V	V&0.75
Los Morales	Spain	W	Morales	2	28	200	22	26	V	0.75
Santa Eugenia	Spain	H	Xallas	17	84	290	225	254	0.05	0.75&0.35
Los Canchales	Spain	FW	Lácara	15	32	240	25	54	V	0,5&0.80
Maroño	Spain	W	Izoria and Idas	2	53	182	80	91	0.05	V&0.75
Hervás	Spain	W	Hervás	1	33	210	24	43	0.15	0.7
Burguillo del Cerro	Spain	W	Ribera de los Montes	3	24	167	25	33	V	0,13&0.60
La Puebla de Cazalla	Spain	I	Corbones	74	71	220	205	220	V&0.20	0.8
Belén-Cagüela	Spain	F	Belén	1	31	160	24	29	0.05	0.75

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Belén-Gato	Spain	F	Belén	1	34	158	36	41	0.05	0.75
Caballar I	Spain	F	Belán	1	16	98	6	7	0.05	0.75
Amatisteros III	Spain	F	Belén	1	19	75	4	5	0.05	0.75
Belén-Flores	Spain	F	Belén	1	28	87	10	12	0.05	0.75
Urdalur	Spain	W	Alzania	5	58	396	159	208	V	0.75
Arriarán	Spain	W	Arriarán	3	58	206	110	113	0.05	0.7
Cenza	Spain	H	Cenza	43	49	609	200	225	V	0.122&0.75
Sierra Brava	Spain	I	Pizarroso	232	54	835	277	340	0.05	0.75
Boqueron	Spain	F	Rambla del Boqueron	13	58	290	137	145	0.05	0.73
Queiles y Val	Spain	F	Val	25	82	375	480	520	V&0.33	0.8
Atance	Spain	I	Salado	35	45	184	65	75	V	0.8
Rialb	Spain	IW	Segre	402	99	630	980	1016	0,15&0.35	0,4&0.65
El Esparragal	Spain		Viar	5	21	383	62	89	0.3	0.9
La Breña II	Spain	I	Guadiato	823	119	685	1441	1600	0.05	0.75
El Puente de Santolea	Spain		Guadalope	18	44	183	52	61		
Pak Mun	Thailand	H	Mun	225	26	323	48	50	V	V&0.80
Mae Suai	Thailand	I	Mae Suai	73	59	340	300	350	0.15	0.80
Tha Dan	Thailand	I	Nakhon Nayok	224	95	2600	4900	5400	V&0.40	0.80
Ma Dua	Thailand	FI	Khlong Ma Dua	85	92	537	900		V&0.2	0.72
R'mil	Tunisia	I	R'mil	44	18	260	64	160	V	0.90
Moula	Tunisia	W	Bou Terfess	26	84	324	400	422	V	
Sucati	Turkey	H	Güredin Creek	9	36	192	55	60	V	0.8
Çindere	Turkey	HI	Buyuk Menderes	85	107	280	1500	1680	0.7	0.7
Beydag	Turkey	I	Kucukmenderes	248	96	800	2350	2650	0.35	0.8
Feke II	Turkey	H	Göksu	63	70	236	232	0	0.07	0.8

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions Height (m)	Dimensions Length (m)	Volume RCC (m^3x10^3)	Volume Total (m^3x10^3)	Facings Upstream Slope	Facings Downstream Slope
Burç	Turkey	H	Göksu	27	47	153	49	68		
Çine	Turkey	FHI	Çine	350	137	300	1560	1650	0,1&0.20	0.85
Simak	Turkey	H	Robozik Deresi		67	198	245	265		
Camlica III	Turkey	FH	Kucukmenderes	1	52	800	153	219	0.7	0.7
Safad	UAE	GI		1	19	100	9	10	V	0.8
Showkah	UAE	GI		1	24	105	18	20	0.10	0.8
Willow Creek	USA	FR	Willow Creek	17	52	543	331	331	V	0.8
Middle Fork	USA	FW	Middle Fork	1	38	125	42	43	V	0.8
Winchester (now Carroll E. Ecton)	USA	W	Upper Howard Creek	2	23	363	24	27	V	V&1.00
Galesville	USA	FIRW	Cow Creek	52	50	290	161	171	V	0.8
Grindstone Canyon	USA	W	Grindstone	2	42	432	88	96	V	0.75
Monksville	USA	W	Wanaque	27	48	670	219	232	V	V&0.78
Lower Chase Creek	USA	F	Lower Chase Creek	1	20	122	14	22	V	0.7
Upper Stillwater	USA	IW	Rock Creek	37	91	815	1125	1281	V	0,32&0.60
Elk Creek (as halted)	USA	F	Elk Creek	125	35	365	266	348	V	0.8
Stagecoach	USA	HIRW	Yampa	42	46	116	34	39	V	0.8
Stacy - spillway (now S.W. Freese)	USA	W	Colorado	700	31	173	89	158	V	0.831
Quail Creek South	USA	W	Quail Creek	50	42	610	130	150	V	V&0.85
Freeman diversion	USA	G	Santa Clara	-	17	366	101	110	V	0.8
Nickajack Auxillary Spillway	USA	H	Tennessee	311	17	427	79	79	0.25	0.6
Cuchillo Negro	USA	F	Cuchillo Negro	-	50	186	75	82	V	0.9
Victoria replacement	USA	H	West branch	13	37	100	36	40	V	0.8
Alan Henry Spillway	USA	W	Double Mountain Fork	140	25	84	22	23	V	1.1
Town Wash (now Jim Wilson) Detention	USA	F	Town Wash	-	18	264	43	45	V	1.5
C.E. Siegrist	USA	W	Mill	4	40	213	69	70	V	0.8
Zintel Canyon	USA	F	Zintel	3	39	158	54	55	V	0.85

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Elmer Thomas - replacement	USA	R	Little Medicine Creek	10	34	128	29	34	V	0.64
Spring Hollow	USA	W	off-stream	12	74	302	222	223	V	0.8
Hudson River N°11	USA	W	Mountain Creek	-	21	168	26	28	V	0.8
Rocky Gulch	USA	P	Rocky Gulch	-	18	55	6	7	V	0.8
New Peterson Lake	USA	W	Tributary of Cache La Poudre	3	21	70	7	8	V	0.8
Big Haynes	USA	W	Big Haynes Creek	-	27	427	72	74	V	0.8
Tie Hack	USA	W	South Fork Clear Creek	3	41	170	62	69	V	0.8
Penn Forest	USA	W	Wild Creek	2	49	610	283	283	V	0.5
Bullard Creek	USA	F	Bullard Creek	1	16	110	7	7	V	V&0.75
Barnard Creek Canyon Debris Dam	USA	F	Barnard Creek	-	18	46	3	3	V	0.75
Pickle Jar	USA	W		1	16	57	3.31	3.31	V	0.8
Trout Creek	USA	IR	Trout Creek	1	31	38	9	10	V	0.8
Pajarito Canyon	USA	F	Pajarito	8	36	112	48	48	V	1
North Fork Hughes River	USA	FRW	North Fork Hughes River	1480	26	200	65	65	V	0.8
Hunting Run	USA	W	Hunting Run	2	25	720	105	105	V	
Randleman Lake	USA	RW	Deep	84	31	280	70	76	V	0.75
Olivenhain	USA	W	Escondido Creek	30	97	788	1070	1140	V	0.8
Saluda dam remediation	USA	H	Saluda	1970	65	2439	1004	1410		
Pine Brook	USA	W		1	26	170	27	30	V	
Elkwater Fork	USA	W	Tygart Tributory	3	39	204	106	113	V	0.8
Hickory Log Creek	USA	W	Hickory Log Creek	1	55	290	165	0	V	0.8
Taum Sauk	USA	H	Water source - East Fork of Black River	6	49	2060	2100	2300	0.6	0.6

Table A.1 General Description of RCC Dams (continued)

Dam/Project	Country	Purpose	River	Reservoir Capacity (m^3x10^6)	Dimensions		Volume		Facings	
					Height (m)	Length (m)	RCC (m^3x10^3)	Total (m^3x10^3)	Upstream Slope	Downstream Slope
Deep Creek N°5D	USA	FW	Deep Creek	15	22	226	39	45	V	0.8
Thornton Gap (Tollway)	USA	F		1	35	69	25	25	V	
San Vicente Dam Raise	USA	W		299	67	474	0	0	V	
Portugues	USA	F	Portugues	12	67	375	270	279	V	0.35
Pleikrong	Vietnam	H	Po Ko	1048	71	495	326	450	V	0.8
A Vuong	Vietnam	H	Vugia Thubon	340	83	240	260	350	V	0.8
Dinh Binh	Vietnam	FHIW	Kon	226	55	571	183	430	V	0.75
Se San 4	Vietnam	H	Poko	173	74	834	753	1300	V	0.8
Son La	Vietnam	FH	Sond Da (Black River)	9600	139	900	2700	4800	V	0.8
Ban Ve	Vietnam	H	Ca	1500	136	480	1520	1750	V&0.30	0.85
Dong Nai 3	Vietnam	FH	Dong Nai	1690	108	594	1138	1235	V	0.75
Ban Chat	Vietnam	H	Nam Mu	2138	130	425	1200	1600	V	0.8
Dong Nai 4	Vietnam	H	Dong Nai	337	128	481	1305	1370	V	0.8
Nuoc Trong	Vietnam	HI	Tra Kluc	290	69	454	450	600	V	
Dong Nai 2	Vietnam	H	Dong Nai	281	80	429	786	1025		
Song Tranh 2	Vietnam	H	Song Tranh	721	97	640	1030	1315	V	0.8
Dak Drinh	Vietnam	H	Dak Drinh	249	100	466	788	0		
Dak Mi 4	Vietnam	H	Dak Mi		90	0	720	0		
Song Bung 4	Vietnam	H	Bung	511	114	367	764	954	0.4	0.8
Trung Son	Vietnam	H	Ma	349	88	353	810	916	0.35	0.8
Huong Dien	Vietnam	H	Bo		83	0	260	400		
Song Bung 2	Vietnam	H	Bung		95	0	0	0	0.4	0.8

Table A.2 Mixture Content of RCC Dams

Dam/Project	Cement (kg/m^3)	Pozzolan (kg/m^3)	Pozzolan Type	Water (kg/m^3)	Water / (Cement+Pozzolan) Ratio (w/c)
Beni Haroun	82	143	F	101	0.45
Koudiat Acerdoune	77	87	F		
Boussiaba	112	28	F		
Capanda	70	100	M		
Capanda Mix. 1	80			102	1.28
Capanda Mix. 2	70			102	1.46
Capanda Mix. 3	80			115	1.44
Capanda Mix. 4	70			120	1.71
Capanda Mix. 5	75			120	1.60
Urugua-i	60	0		100	1.67
Copperfield	80	30	F		
Craigbourne	70	60	F		
Wright's Basin	145	73	F		
New Victoria	79	160	F		
Kroombit	82	107	F		
Burton Gorge	85	0			
Lower Molonglo Bypass Storage	96	64	F		
Loyalty Road flood retarding basin	80	0	S		
Cadiangullong	90	90	F		
Paradise (Burnett River)	63				
Meander	70				
North Para	60	160	F		
Wyaralong	85	85	F		
Enlarged Cotter	70	120	F		
Chalillo	80	25	N		
La Cañada	140	100	N		
Saco de Nova Olinda	55	15	N		
Caraibas	58	16	N		
Gameleira	65	0			
Pelo Sinal	100	0			
Acauã	56	14	N		

Table A.2 Mixture Content of RCC Dams (continued)

Varzea Grande	56	14	N		
Cova da Mandioca	80	0			
Trairas	80	0			
Canoas	64	16	N		
Jordão	65	10	N		
Belo Jardim	58	15	N		
Rio do Peixe	120&90	0			
Salto Caxias	80	20	F		
Val de Serra	60	30	F		
Jucazinho	64	16	N		
Guilman- Amorin	80	20	N		
Bertarello	72	18	N		
Rosal	45	55	S		
Ponto Novo	72	18	N		
Santa Cruz do Apodi	80	0			
Tucuruí - 2nd Phase	70	30	N		
Dona Francisca Mix.1	55	30	F	140	1.65
Dona Francisca Mix.2	55	30	F	135	1.59
Dona Francisca Mix.3	58	32	F	140	1.56
Dona Francisca Mix.4	58	32	F	135	1.50
Dona Francisca Mix.5	65	35	F	136	1.36
Dona Francisca Mix.6	58	32	F	148	1.64
Dona Francisca Mix.7	62	32	F	149	1.59
Dona Francisca Mix.8	62	32	F	149	1.59
Dona Francisca Mix.9	62	32	F	144	1.53
Dona Francisca Mix.10	65	35	F	145	1.45
Umari	70	0			
Pedras Altas	80	0			
Pirapana	90	0			
Cana Brava	45	55	S		
Castanhão	85	0			
Lajeado	30	40	S		
Lajeado Mix No.1	70	0		135	1.93
Lajeado Mix No.2	100	0		140	1.40
Lajeado Mix No.3	120	0		146	1.22
Lajeado Mix No.4	140	0		140	1.00
Lajeado Mix No.5	160	0		160	1.00
Lajeado Mix No.6	180	0		180	1.00
Lajeado Mix No.7	180	0		180	1.00

Table A.2 Mixture Content of RCC Dams (continued)

Serra do Facão	90	0			
Fundão	80	0			
Candonga	90	0			
Pindobaçu	70	0			
Bandeira de Malo	70	0			
Santa Clara - Jordão	60	30	F		
Estreito	64	16	N		
Lac Robertson	85	85	F		
Grand Falls spillway	130	75	F		
Pangue	80	100	N		
Ralco	137	58	N	145	0.74
Ralco	95	40	N	145	1.07
Ralco	116	49	N	145	0.88
Ralco Lab. Mix.No.1	95	40	N		
Ralco Lab. Mix.No.2	102	43	N		
Ralco Lab. Mix.No.3	116	49	N		
Ralco Lab. Mix.No.4	123	52	N		
Kengkou	60	120	F		
Kengkou	60	80	F		
Rongdi	90	140	F		
Rongdi	69	111	F		
Longmentan Nº1	72	82	F		
Longmentan Nº1	54	86	F		
Tianshengqio	55	85	F		
Tongjiezi (with Niurixigou saddle dam)	79	79	F		
Tongjiezi (with Niurixigou saddle dam)	82	83	F		
Tianshenqiao Nº2	79	79	F		
Yantan	55	104	F	90	0.57
Shuikou	60	110	F		
Shuikou	70	90	F		
Wan’an	65	105	F		
Guangzhou PSS - Lower dam	62	108	F		
Suoshai					
Three Gorges Mix.1	119	79	F	89	0.45
Three Gorges Mix.2	98	98	F	88	0.45
Three Gorges Mix.3	77	116	F	87	0.45

Table A.2 Mixture Content of RCC Dams (continued)

Three Gorges Mix.4	107	71	F	89	0.50
Three Gorges Mix.5	88	88	F	88	0.50
Three Gorges Mix.6	70	104	F	87	0.50
Three Gorges Mix.7	97	65	F	89	0.55
Three Gorges Mix.8	80	80	F	88	0.55
Three Gorges Mix.9	63	95	F	87	0.55
Three Gorges Mix.10	96	64	F	72	0.45
Three Gorges Mix.11	79	79	F	71	0.45
Three Gorges Mix.12	62	93	F	70	0.45
Three Gorges Mix.13	86	58	F	72	0.50
Three Gorges Mix.14	71	71	F	71	0.50
Three Gorges Mix.15	56	84	F	70	0.50
Three Gorges Mix.16	79	52	F	72	0.55
Three Gorges Mix.17	65	65	F	71	0.55
Three Gorges Mix.18	51	76	F	70	0.55
Jinjiang	70	80	F		
Puding	85	103	F		
Puding	54	99	F		
Shuidong	50	90	F		
Daguangba	55	96	F		
Shanzai	65	125	F		
Shanzai	55	95	F		
Wenquanpu	110	68	F		
Wenquanpu	69	85	F		
Xibingxi	80	120	F		
Xibingxi	79	105	F		
Guanyinge (Kwan-in-Temple)	91	39	F		
Guanyinge (Kwan-in-Temple)	112	48	F		
Shimantan	98	98	F		
Shimantan	51	107	F		
Bailongtan	73	110	F		
Bailongtan	99	60	F		
Mantaicheng	60	120	F		
Wanyao	64	96	F		
Wanyao	60	90	F		
Shuangxi	90	110	F		
Shuangxi	55	105	F		
Shibanshui	126	84	F		
Shibanshui	60	90	F		
Shibanshui	50	100	F		

Table A.2 Mixture Content of RCC Dams (continued)

Taolinkou	135	70	F		
Taolinkou	70	85	F		
Yongxi N°3	115	95	F		
Yongxi N°3	80	90	F		
Huatan	78	95	F		
Huatan	74	90	F		
Changshun	134	89	F		
Changshun	72	48	F		
Fenhe N°2	127	84	F		
Fenhe N°2	60	93	F		
Jiangya	87	107	F		
Jiangya	64	96	F		
Jiangya	46	107	F		
Songyue (1st Stage)	80	100	F		
Baishi	72	58	F		
Hongpo	54	99	F		
Gaobazhou	123	100	F		
Gaobazhou	86	86	F		
Yanwangbizi	64	118	F		
Yushi	70	70	F		
Shankou N°3	105	86	F		
Shankou N°3	63	80	F		
Shapai Mix 1	115	77	F		
Shapai Mix 2	91	91	F		
Shimenzi Mix 1	93	110	F		
Shimenzi Mix 2	62	110	F		
Longshou N°1	96	109	F		
Longshou N°1	58	113	F		
Dachaoshan	94	94	N		
Dachaoshan	67	101	N		
Mianhuatan Mix 1	82	100	F		
Mianhuatan Mix 2	59	88	F		
Mianhuatan Mix 3	48	88	F		
Mianhuatan Lab Mix No.1	100	180			
Mianhuatan Lab Mix No.2	150	180			

Table A.2 Mixture Content of RCC Dams (continued)

Mianhuatan Lab Mix No.3	200	180			
Mianhuatan Lab Mix No.4	200	90			
Mianhuatan Lab Mix No.5	250	90			
Mianhuatan Lab Mix No.6	300	28			
Helong	113	113	F		
Xiao Yangxi (and saddle dam)	138	113	F		
Xiao Yangxi (and saddle dam)	60	90	F		
Wanmipo	86	103	F		
Wanmipo	68	83	F		
Linhekou	74	111	F	87	0.47
Linhekou	66	106	F	81	0.47
Zhouning	67	100	F		
Zhouning	50	92	F		
Zhaolaihe	84	126	F		
Zhaolaihe	126	103	F		
Wenquangpu	95	57	F		
Wenquangpu	110	58	F		
Xihe					
Suofengying	64	95	F		
Zaoshi	53	99	F		
Zaoshi	83	102	F		
Baisha					
Zhouba	110	73	F		
Zhouba	66	66	F		
Tukahe	65	110	S		
Tukahe	93	113	S		
Baise	80	132	F		
Baise	50	110	F		
Dahuashui	81	81	F		
Dahuashui	94	94	F		
Bailianya	72	108	F		
Bailianya	56	84	F		
Huizhou PSS - Upper Dam	64	125	F		
Jing Hong	64	93	S		
Jing Hong	93	93	S		

Table A.2 Mixture Content of RCC Dams (continued)

Pengshui	64	96	F		
Pengshui	81	121	F		
Huanghuazhai	52	96	F		
Longtan	99	121	F		
Longtan	86	109	F		
Longtan Trial Mix 1 with retarding superplasticizer	90	101	F	80	0.42
Longtan Trial Mix 2 with air entering agent	90	101	F	80	0.42
Longtan Trial Mix 3 with retarding superplasticizer	56	104	F	80	0.50
Longtan Trial Mix 4 with air entering agent	56	104	F	80	0.50
Guangzhao	61	91	F		
Guangzhao	77	87	F		
Gelantan	77	77	S		
Silin	66	100	F		
Silin	89	109	F		
Jin’anqiao	72	108	F		
Jin’anqiao	96	117	F		
Longkaikou	83	101	F		
Longkaikou	60	90	F		
Porce II	132	88	N		
Porce II	120	80	N		
Porce III Lab.Mix No.1	85	0			
Porce III Lab.Mix No.2	125	0			
Miel I Mix.1	150	0			
Miel I Mix.2	125	0			
Miel I Mix.3	100	0			
Miel I Mix.4	85	0			
Peñas Blancas	90	35	N		
Pirris	100	100	N		
Pirris	80	80	N		
Contraembalse de Monción	72~88	0			

Table A.2 Mixture Content of RCC Dams (continued)

Panalito	98	8	M		
Villarpando	90			105	1.17
Toker	110	85	F		
Gibe III	72	48	S		
Les Olivettes	0	130	R		
Riou	0	120	R		
Choldocogagna	0	110	R		
Villaunur	0	90	R		
Sep	0	120	R		
La Touche Poupard	0	115	R		
Petit Saut	0	120	R		
Marathia	55	15	N		
Ano Mera	55	15	N		
Platanovryssi	50	225	C		
Steno	55	5	N		
Lithaios	50	10	N		
Koris Yefiri (Maiden's Bridge)	50	10	N		
Valsamiotis	60	0			
Concepción	90	0		93	1.03
Nacaome	64	21	N		
Nordlingaalda Mix.1	80	0		134	1.68
Nordlingaalda Mix.2	105	0		136	1.30
Nordlingaalda Mix.3	133	0		135	1.02
Nordlingaalda Mix.4	213	0		138	0.65
Ghatghar (Upper dam)	88	132	F		
Ghatghar (Lower dam)	75	150	F		
Ghatghar pumped storage Mix No.1	108	72	F	117	0.65
Ghatghar pumped storage Mix No.2	90	90	F	117	0.65
Ghatghar pumped storage Mix No.3	72	108	F	117	0.65
Ghatghar pumped storage Mix No.4	54	126	F	117	0.65

Table A.2 Mixture Content of RCC Dams (continued)

Ghatghar pumped storage Mix No.5	120	80	F	116	0.58
Ghatghar pumped storage Mix No.6	100	100	F	116	0.58
Ghatghar pumped storage Mix No.7	80	120	F	116	0.58
Ghatghar pumped storage Mix No.8	60	140	F	116	0.58
Ghatghar pumped storage Mix No.9	154	66	F	115	0.52
Ghatghar pumped storage Mix No.10	132	88	F	115	0.52
Ghatghar pumped storage Mix No.11	110	110	F	115	0.52
Ghatghar pumped storage Mix No.12	88	132	F	115	0.52
Ghatghar pumped storage Mix No.13	66	154	F	115	0.52
Ghatghar pumped storage Mix No.14	144	96	F	114	0.48
Ghatghar pumped storage Mix No.15	120	120	F	114	0.48
Ghatghar pumped storage Mix No.16	96	144	F	114	0.48
Ghatghar pumped storage Mix No.17	72	168	F	114	0.48
Krishna Weir (Srisailam)	75	75	F		
Middle Vaitarna	75	135	F		
Balambano	81	54	F		
Pie Pol	130	0			
Jahgin	105	90	N		
Jahgin	160	90	N		
Jahgin Stage 1 Mix 1	70	125	Khash natural pozzolan	140	0.72

Table A.2 Mixture Content of RCC Dams (continued)

Jahgin Stage 1 Mix 2	95	100	Khash natural pozzolan	140	0.72
Jahgin Stage 1 Mix 3	120	75	Khash natural pozzolan	140	0.72
Jahgin Stage 1 Mix 4	145	50	Khash natural pozzolan	140	0.72
Jahgin Stage 1 Mix 5	170	25	Khash natural pozzolan	140	0.72
Jahgin Stage 1 Mix 6	190	0	Khash natural pozzolan	140	0.74
Jahgin Stage 2 RCC 1-1 with Khash Natural Pozzolan	150	75	Khash natural pozzolan	130	0.58
Jahgin Stage 2 RCC 1-2 with Khash Natural Pozzolan	165	60	Khash natural pozzolan	130	0.58
Jahgin Stage 2 RCC 1-3 with Khash Natural Pozzolan	180	45	Khash natural pozzolan	130	0.58
Jahgin Stage 2 RCC 2-1 with Khash Natural Pozzolan	90	105	Khash natural pozzolan	130	0.67
Jahgin Stage 2 RCC 2-2 with Khash Natural Pozzolan	105	90	Khash natural pozzolan	130	0.67
Jahgin Stage 2 RCC 2-3 with Khash Natural Pozzolan	120	75	Khash natural pozzolan	130	0.67
Jahgin Stage 2 RCC 1-1 with Low-Lime Flyash	95	125	Low-Lime Flyash	130	0.59
Jahgin Stage 2 RCC 1-2 with Low-Lime Flyash	110	110	Low-Lime Flyash	130	0.59

Table A.2 Mixture Content of RCC Dams (continued)

Jahgin Stage 2 RCC 1-3 with Low-Lime Flyash	125	95	Low-Lime Flyash	130	0.59
Jahgin Stage 2 RCC 2-1 with Low-Lime Flyash	70	125	Low-Lime Flyash	130	0.67
Jahgin Stage 2 RCC 2-2 with Low-Lime Flyash	85	110	Low-Lime Flyash	130	0.67
Jahgin Stage 2 RCC 2-3 with Low-Lime Flyash	100	95	Low-Lime Flyash	130	0.67
Zirdan	98	42	N		
Badovli	160			115	0.72
Javeh	87	38	N		
Sa Stria Mix.1	58	34 135	N F	139	
Sa Stria Mix.2	67	39 106	N F	123	
Sa Stria Mix.3	69	41 105	N F	140	
Sa Stria Mix.4	72	43 95	N F	124	
Sa Stria Mix.5	75	44 93	N F	140	
Sa Stria Mix.6	92	54 77	N F	140	
Sa Stria Mix.7	122	72 40	N F	142	
Sa Stria Mix.8	82	148	N	133	0.58
Sa Stria Mix.9	92	138	N	129	0.56
Sa Stria Mix.10	104	126	N	124	0.54
Sa Stria Mix.11	71	58 101	N L	124	
Sa Stria Mix.12	81	66 83	N L	120	
Sa Stria Mix.13	92	75 63	N L	117	
Shimajigawa	84	36	F	105	0.88
Tamagawa	91	39	F	95	0.73

Table A.2 Mixture Content of RCC Dams (continued)

Mano	96	24	F	103	0.86
Shiromizugawa	96	24	F	102	0.85
Asahi Ogawa	96	24	F	94	0.78
Nunome	78	42	F	95	0.79
Nunome Mix 1	140	0	F	117	0.84
Nunome Mix 2	98	42	F	113	0.81
Nunome Mix 3	91	49	F	111	0.79
Nunome Mix 4	84	56	F	107	0.76
Pirika	84	36	F	90	0.75
Dodairagawa	96	24	F	102	0.85
Asari	96	24	F	103	0.86
Kamuro	96	24	F	103	0.86
Sakaigawa	84	36	F	103	0.86
Sabigawa (lower dam)	91	39	F	95	0.73
Ryumon	91	39	F	83	0.64
Tsugawa	96	24	F	100	0.83
Miyatoko	96	24	F	98	0.82
Kodama	91	36	S	102	0.80
Hinata	84	36	F	100	0.83
Miyagase	91	39	F	95	0.73
Yoshida	84	36	F	95	0.79
Chiya	91	39	F	103	0.79
Ohmatsukawa	91	39	F	105	0.81
Satsunaigawa	78	42	S	83	0.69
Shiokawa	96	24	F	100	0.83
Urayama	91	39	F	85	0.65
Shimagawa	84	36	F	100	0.83
Hiyoshi	84	36	F	83	0.69
Tomisato No.1	84	36	F	90	0.75
Tomisato No.2	72	48	F	90	0.75
Takisato	84	36	F	88	0.73
Kazunogawa	84	36	F	90	0.75
Hayachine	84	36	F	97	0.81
Gassan	91	39	F	87	0.67
Kubusugawa	84	36	F	97	0.81
Nagashima sediment dam	40	50	S		
Ohnagami	84	36	F	103	0.86
Origawa	91	39	F	93	0.72
Shinmiyagawa	91	39	F	95	0.73

Table A.2 Mixture Content of RCC Dams (continued)

Ueno	77	33	F	89	0.81
Ueno	70	30	F		
Chubetu	84	36	F	76	0.63
Fukuchiyama	84	36	F	90	0.75
Kutani	84	36	F	105	0.88
Koyama	84	36	S	100	0.83
Takizawa	84	36	F	85	0.71
Takizawa	72	48	F	85	0.71
Hattabara	84	36	F	90	0.75
Kido	84	36	F	103	0.86
Nagai	91	39	F	100	0.77
Toppu	84	36	F	86	0.72
Kasegawa	84	36	F	99	0.83
Yubari Syuparo	91	39	F	85	0.65
Tannur Mix 1	125	75	N		
Tannur Mix 2	120	50	N		
Wala	120	0			
Wala	110	0			
Mujib	85	0		140	1.65
Sama El-Serhan	96	85	N	90	0.50
Al Wehdah	70	60	F		
Al Wehdah	60	60	F		
Buchtarma	135	80	F		
Tashkumyr	90	30	N		
Nakai, part of Nam Theun 2 HPP	100	100	F		
Nam Gnouang (Theum Hinboun Expansion)	90	100	C		
Kinta	100	100	F		
Batu Hampar	65	120	F		
Bengoh	65	125	F		
La Manzanilla	135	135	N		
Trigomil	148	47	F		
Vindramas	100	100	M		
San Lazaro	100	220	M		
San Lazaro	90	220	M		
San Rafael	90	18	N		
Las Blancas	100	100	F		

Table A.2 Mixture Content of RCC Dams (continued)

Rompepicos at Corral des Palmas	65	35	F		
Amata	120	0			
El Zapotillo	50~70	60~80			
El Zapotillo Mix 1	110	221	L	86	0.26
El Zapotillo Mix 2	130	220	L	87	0.25
El Zapotillo Mix 3	150	218	L	87	0.24
Ain al Koreima	70	30	S		
Ain al Koreima	140	60	S		
Rouidat Amont (Rwedat)	100	15	N		
Aoulouz	120	0	M		
Aoulouz	90	0	M		
Joumoua	105	45	N		
Imin el Kheng	100	20	N		
Imin el Kheng	110	20	N		
Sahla	85	15	N		
Sahla	125	25	N		
Enjil	110	0	N		
Enjil	150	0	N		
Bouhouda	100	0	N		
Bouhouda	120	0	N		
Bab Louta	65	15	N		
Bab Louta	80	20	N		
Ahl Souss (Ait M'Zal)	80	0			
Ahl Souss (Ait M'Zal)	100	0			
Hassan II (Sidi Said)	65	15	N		
Hassan II (Sidi Said)	80	20	N		
Oued R'Mel	100	0			
Sidi Yahya (Ain Kwachia)	105	0			
Sehb el Merga	70	30	N		
El Maleh	120	0			
Ait Mouley Ahmed	70	30	N		
Yeywa	75	145	N		
Yeywa Stage I-A Mix 1	70	140	P1-4		
Yeywa Stage I-A Mix 2	70	140	P2-5		
Yeywa Stage I-A Mix 3	70	140	P2-7		

Table A.2 Mixture Content of RCC Dams (continued)

Yeywa Stage I-A Mix 4	70	140	P2-9		
Yeywa Stage I-A Mix 5	70	140	P1-9		
Yeywa Stage I-B Mix 1	70	140	P1-9		
Yeywa Stage I-B Mix 2	90	130	P1-9		
Yeywa Stage I-B Mix 3	90	130	P1-9		
Yeywa Stage I-B Mix 4	110	110	P1-9		
Yeywa Stage I-B Mix 5	130	90	P1-9		
Yeywa Stage I-B Mix 6	150	70	P1-9		
Yeywa Stage II Mix 1	55	165	P1-9		
Yeywa Stage II Mix 2	60	160	P1-9		
Yeywa Stage II Mix 3	65	155	P1-9		
Yeywa Stage II Mix 4	70	150	P1-9		
Yeywa Stage II Mix 5	75	145	P1-9		
Upper Paung Laung	85	145	N		
Wadi Dayqah	126	54	M		
Wadi Dayqah	112	48	M		
Mangla Emergency Spillway Control Weir	60	120	S		
Gomal Zam	91	91	F		
Changuinola 1	70	145	F		
Changuinola 1	65	150	F		
Capillucas	65	90	N		
Pedrógão	55	165	F		
Pedrógão Mix 1	70	130	F	120	0.60
Pedrógão Mix 2	70	130	F	130	0.65
Pedrógão Mix 3	70	130	F	130	0.65
Pedrógão Mix 4	50	130	F	130	0.72
Pedrógão Mix 5	40	120	F	120	0.75
Vadeni	125	0			
Tirgu Jiu	125	0			
Bureiskaya	95~110	25~30	N		
De Mist Kraal	58	58	F		
Arabie	36	74	S		
Zaaihoek	36	84	S		
Knellpoort	61	142	F		
Spitskop	91	92	F		

Table A.2 Mixture Content of RCC Dams (continued)

Wolwedans	58	136	F		
Wriggleswade	44	66	F		
Glen Melville	65	65	F		
Thornlea	38	87	S		
Taung	44	66	F		
Paxton	70	100	F		
Qedusizi (Mount Pleasant)	46	108	S		
Inyaka	60	120	F		
Nandoni (formerly Mutoti)	54	129	F		
Bramhoek	70	95	F		
De Hoop	62	145	F		
Castilblanco de los Arroyos	102	86	F	102	0.54
Los Morales	80	140	F	108	0.49
Los Morales	74	128	F	98	0.49
Santa Eugenia	88	152	F	100	0.42
Santa Eugenia	72	145	F	90	0.41
Los Canchales	84	156	F	105	0.44
Los Canchales	70	145	F	100	0.47
Maroño	80	170	F	100	0.40
Maroño	65	160	F	98	0.44
Hervás	80	155	F	95	0.40
Burguillo del Cerro	80	135	F	85	0.40
La Puebla de Cazalla	80	130	F	113	0.54
La Puebla de Cazalla	85	137	F	127	0.57
Erizana	90	90		115	0.64
Belén-Cagüela	75	109	F	110	0.60
Belén-Gato	73	109	F		
Caballar I	73	109	F		
Amatisteros I	73	109	F	105	0.58
Belén-Flores	73	109	F		
Urdalur	53	123	F		
Urdalur	72	108	F	90	0.50
Arriarán	85	135	F	100	0.45
Cenza	70	130	F	95	0.48
Sierra Brava	80	140	F	95	0.43

Table A.2 Mixture Content of RCC Dams (continued)

Guadalemar	60	125	F	100	0.54
Rambla	55	130	F	94	0.51
Queiles y Val	80	100	F	100	0.56
Atance	57	133	F	109	0.57
Rialb	70	130	F	95	0.48
El Esparragal	68	157	F	112.5	0.50
El Esparragal Mix.1	56	169	F	101	0.45
El Esparragal Mix.2	79	146	F	112.5	0.50
El Esparragal Mix.3	225	0	F	126	0.56
La Breña II	69	115&46	F		
El Puente de Santolea	65	153	F		
Pak Mun	58	124	F	119	0.65
Mae Suai	80	90	F	137	0.81
Tha Dan	90	100	F	115	0.61
Ma Dua	50	150	F	120	0.60
R’mil	100	0			
Moula	120	0			
Sucati	50	100	S		
Çindere	50	20	F		
Beydag	60	30	F		
Feke II	60	60	F		
Feke II	60	50	F		
Burç	65	50	F		
Çine	85	105	F		
Çine	75	95	F		
Simak	95				
Camlica III	88	37	F		
Safad	90	0			
Showkah	90	0			
Camp Dyer	82	81		90	0.55
Willow Creek Mix 1	104	0		110	1.06
Willow Creek Mix 2	104	47		110	0.73
Willow Creek Mix 3	187	80		109	0.41
Willow Creek Mix 4	47	19	F	107	1.62
New Big Cherry	76	76	F	130	0.86
Middle Fork	66	0		95	1.44
Winchester (now Carroll E. Ecton)	104	0			

Table A.2 Mixture Content of RCC Dams (continued)

Galesville Mix 1	53	51	F	113	1.09
Galesville Mix 2	65	68	F	113	0.85
Grindstone Canyon	76	0			
Monksville	64	0			
Lower Chase Creek	64	40	F		
Upper Stillwater Mix 1	94	207	F	89	0.30
Upper Stillwater Mix 2	93	206	F	100	0.33
Upper Stillwater Mix 3	79	173	F	99	0.39
Upper Stillwater Mix 4	79	173	F	94	0.37
Upper Stillwater Mix 5	108	125			
Upper Stillwater Mix 6	72	160			
Elk Creek Mix 1	70	33	F		
Elk Creek Mix 2	56	23	F		
Elk Creek Mix 3	67	17	F		
Stagecoach	71	77	F	138	0.93
Stacy - spillway (now S.W. Freese)	125	62	C	154	0.82
Quail Creek South	80	53	F		
Freeman diversion	125	83	F		
Nickajack Auxillary Spillway	85	119	F		
Cuchillo Negro	77	59	F	135	0.99
Victoria replacement	67	67	C	107	0.80
Alan Henry Spillway	119	59	F		
Town Wash (now Jim Wilson) Detention	107	71	F		
C.E. Siegrist Mix 1	47	47	F	96	1.02
C.E. Siegrist Mix 2	53	42	F	96	1.01
C.E. Siegrist Mix 3	59	42	F	96	0.95
Zintel Canyon Mix 1	178	0		101	0.57
Zintel Canyon Mix 2	74	0		101	1.36
Zintel Canyon Mix 3	74	0		112	1.51
Zintel Canyon Mix 4	59	0			
Zintel Canyon Mix 5	119	0			
Elmer Thomas - replacement	89	89	F		
Spring Hollow	53	53	F		

Table A.2 Mixture Content of RCC Dams (continued)

Hudson River N°11	119	84	F		
Rocky Gulch	184	0			
New Peterson Lake	145	48	F		
Big Haynes	42	42			
Tie Hack	89	83	F		
Penn Forest	58	41	F		
Bullard Creek	148	44	F		
Barnard Creek Canyon Debris Dam	108	84	F		
Pickle Jar	90	0			
Trout Creek	163	0			
Pajarito Canyon	148	0			
North Fork Hughes River	59	59			
North Fork Hughes River	107	65			
Hunting Run	74	37	F		
Randleman Lake	89	104	F		
Olivenhain	74	121	F	124	0.64
Olivenhain Mix.1	74	121	F	118	0.61
Olivenhain Mix.2	74	121	F	123	0.63
Olivenhain Mix.3	74	121	F	132	0.68
Saluda dam remediation primary	74	89	F	149	0.91
Saluda dam remediation Mix 1	104	89	F	160	0.83
Saluda dam remediation Mix 2	89	89	F	154	0.87
Pine Brook	95	59	F	139	0.90
Genesee Dam No.2	107	62	F		0.00
Elkwater Fork Mix 1	59	89	F	103	0.70
Elkwater Fork Mix 2	74	110	F	103	0.56
Hickory Log Creek Mix 1	89	89			
Hickory Log Creek Mix 2	80	98	F	133	0.75
Hickory Log Creek Mix 3	74	104			
Santa Cruz	76	75	F	101	0.67

Table A.2 Mixture Content of RCC Dams (continued)

Taum Sauk	59	59	F		
Deep Creek N°5D	89	89	F		
Thornton Gap (Tollway)	48	79	F		
San Vicente Dam Raise	86	127	F		
Portugues	121	55	F		
Pleikrong	80	210	N		
A Vuong	90	150	N		
Dinh Binh	70	175	F	110	0.45
Dinh Binh	126	141	F	132	0.49
Se San 4	80	160	N		
Son La	60	160	F		
Son La Stage I Mix 0	45	180	F		
Son La Stage I Mix 1	60	170	F		
Son La Stage I Mix 2	85	145	F		
Son La Stage I Mix 3	110	120	F		
Son La Stage I Mix 4	135	95	F		
Son La Stage I Mix 5	160	70	F		
Son La Stage II Mix 1	45	155	F		
Son La Stage II Mix 2	60	140	F		
Son La Stage II Mix 3	75	125	F		
Ban Ve	80	120	N		
Dong Nai 3	75	0			
Ban Chat	60	160	F		
Dong Nai 4	85	95	N		
Nuoc Trong	125	218	N		
Nuoc Trong	80	230	N		
Dong Nai 2	80	120	N		
Dong Nai 2	90	110	N		
Song Tranh 2	70	110	N		
Song Tranh 2	60	115	N		

Table A.2 Mixture Content of RCC Dams (continued)

Dak Drinh	80	115	N		
Dak Mi 4	95	125	N		
Song Bung 4	80	120	N		
Song Bung 4	60	140	N		
Trung Son	80	140	N		
Trung Son	70	150	N		
Huong Dien	90	100	N		
Song Bung 2	80	120	N		
Song Bung 2	60	140	N		
Cindere	50	20	F		
Naras Mix 1	125	0		105	0.84
Naras Mix 2	150	0		105	0.70
Naras Mix 3	175	0		105	0.60
Naras Mix 4	200	0		105	0.53
Silopi Mix 4	100	0		100	1.00
Silopi Mix 1	120	0		100	0.83
Silopi Mix 2	140	0		100	0.71
Silopi Mix 3	160	0		100	0.63
Gökkaya	50	55		67	0.64

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Galesville Mix 1	104	4.00	7.00	0.93	1.19	0.45	0.66	FALSE	FALSE
Galesville Mix 2	133	5.70	9.40	1.09	1.36	0.57	0.80	FALSE	FALSE
Zintel Canyon Mix 1	178	11.20	14.70	1.47	1.66	0.90	1.08	0.90	FALSE
Zintel Canyon Mix 2	74	4.30	7.50	0.96	1.23	0.47	0.69	FALSE	FALSE
Upper Stillwater Mix 1	301	17.70	24.80	1.80	2.09	1.21	1.50	FALSE	FALSE
Upper Stillwater Mix 2	299	23.60	29.00	2.05	2.24	1.46	1.66	FALSE	FALSE
Upper Stillwater Mix 3	233	12.60	17.90	1.55	1.81	0.98	1.22	0.98	1.22
Upper Stillwater Mix 4	252	15.40	21.40	1.69	1.96	1.11	1.37	FALSE	1.37
Upper Stillwater Mix 5	252	14.70	24.20	1.66	2.07	1.08	1.48	1.08	FALSE
Upper Stillwater Mix 6	232	8.40	14.80	1.29	1.66	0.75	1.08	FALSE	FALSE
Willow Creek Mix 1	104	12.80	18.30	1.56	1.83	0.99	1.24	0.99	1.24
Willow Creek Mix 2	151	14.20	27.30	1.63	2.19	1.05	1.60	1.05	FALSE
Willow Creek Mix 3	267	23.50	30.80	2.04	2.31	1.45	1.72	FALSE	FALSE
Willow Creek Mix 4	66	8.10	11.90	1.27	1.51	0.73	0.94	FALSE	FALSE
Ghatghar pumped storage Mix No.1	180	11.00	14.10	1.46	1.63	0.89	1.05	FALSE	FALSE
Ghatghar pumped storage Mix No.5	200	14.40	21.20	1.64	1.95	1.06	1.36	1.06	1.36
Ghatghar pumped storage Mix No.9	220	14.70	24.60	1.66	2.09	1.08	1.50	1.08	FALSE
Ghatghar pumped storage Mix No.14	240	15.00	21.50	1.67	1.96	1.09	1.37	1.09	1.37

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Miel I Mix.1	150		17.00		1.77		1.18	FALSE	1.18
Miel I Mix.2	125		13.50		1.60		1.02	FALSE	FALSE
Miel I Mix.3	100		9.50		1.36		0.81	FALSE	FALSE
Miel I Mix.4	85		8.00		1.26		0.72	FALSE	FALSE
Saluda dam remediation primary	163	4.31	7.76	0.96	1.25	0.47	0.71	FALSE	FALSE
Saluda dam remediation Mix 2	178	7.24	12.41	1.21	1.54	0.67	0.97	FALSE	FALSE
Lajeado Mix No.2	100	8.40	11.10	1.29	1.46	0.75	0.90	FALSE	FALSE
Lajeado Mix No.4	140	13.00	16.50	1.57	1.75	1.00	1.16	1.00	FALSE
Pedrógão Mix 1	200	15.10		1.68		1.10		1.10	FALSE
Pedrógão Mix 4	180	8.00		1.26		0.72		FALSE	FALSE
Pedrógão Mix 5	160	7.80		1.25		0.71		FALSE	FALSE
Capanda Mix. 1	80	8.40	10.00	1.29	1.40	0.75	0.84	FALSE	FALSE
Capanda Mix. 2	70	7.60	9.80	1.24	1.38	0.70	0.83	FALSE	FALSE
Three Gorges Mix.1	198	27.60	36.20	2.20	2.48	1.61	1.90	FALSE	FALSE
Three Gorges Mix.4	178	23.60	32.80	2.05	2.37	1.46	1.79	FALSE	FALSE
Dona Francisca Mix.1	85	4.70	7.90	1.00	1.26	0.50	0.72	FALSE	FALSE
Dona Francisca Mix.3	90	4.80	8.60	1.01	1.31	0.51	0.76	FALSE	FALSE
Sa Stria Mix.5	212	12.30	19.90	1.53	1.90	0.96	1.31	0.96	1.31
Sa Stria Mix.6	223	14.10	21.40	1.63	1.96	1.05	1.37	1.05	1.37
Nordlingaalda Mix.1	80	9.20	15.00	1.35	1.67	0.79	1.09	FALSE	FALSE
Nordlingaalda Mix.2	105	15.00	22.00	1.67	1.98	1.09	1.39	1.09	1.39
Nordlingaalda Mix.3	133	22.50	31.00	2.00	2.31	1.41	1.73	FALSE	FALSE
Nordlingaalda Mix.4	213	45.50	57.50	2.74	3.05	2.19	2.52	FALSE	FALSE

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Longtan Trial Mix 1	191	27.30	42.60	2.19	2.66	1.60	2.10	FALSE	FALSE
Longtan Trial Mix 3	160	16.40	26.40	1.74	2.15	1.16	1.56	FALSE	FALSE
Longshou Mix 1	205	25.80	34.40	2.13	2.42	1.54	1.84	FALSE	FALSE
Longshou Mix 2	171	20.80	27.50	1.94	2.19	1.35	1.60	FALSE	FALSE
Camp Dyer	163	10.10		1.40		0.84		FALSE	FALSE
Middle Fork	66	8.80	11.40	1.32	1.48	0.77	0.91	FALSE	FALSE
Stacy Spillway	187	18.10	21.40	1.82	1.96	1.23	1.37	FALSE	1.37
Upper Stillwater Mix 1	301	17.70	24.80	1.80	2.09	1.21	1.50	FALSE	FALSE
Upper Stillwater Mix 2	299	23.60	29.00	2.05	2.24	1.46	1.66	FALSE	FALSE
Upper Stillwater Mix 3	252	14.70	24.20	1.66	2.07	1.08	1.48	1.08	FALSE
Upper Stillwater Mix 4	252	15.40	21.40	1.69	1.96	1.11	1.37	FALSE	1.37
Upper Stillwater Mix 5	233	12.60	17.90	1.55	1.81	0.98	1.22	0.98	1.22
Upper Stillwater Mix 6	232	8.40	14.80	1.29	1.66	0.75	1.08	FALSE	FALSE
Ghatghar pumped storage Mix No.1	180	11.00	14.10	1.46	1.63	0.89	1.05	FALSE	FALSE
Ghatghar pumped storage Mix No.2	180	9.60	13.00	1.37	1.57	0.82	1.00	FALSE	FALSE
Ghatghar pumped storage Mix No.3	180	9.00	12.70	1.33	1.55	0.78	0.98	FALSE	FALSE
Ghatghar pumped storage Mix No.4	180	6.80	10.50	1.18	1.43	0.65	0.87	FALSE	FALSE

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m$^{3)}$	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Ghatghar pumped storage Mix No.5	200	14.40	21.20	1.64	1.95	1.06	1.36	1.06	1.36
Ghatghar pumped storage Mix No.6	200	11.90	19.50	1.51	1.88	0.94	1.29	0.94	1.29
Ghatghar pumped storage Mix No.7	200	9.30	15.00	1.35	1.67	0.80	1.09	FALSE	FALSE
Ghatghar pumped storage Mix No.8	200	7.30	12.40	1.21	1.54	0.68	0.97	FALSE	FALSE
Ghatghar pumped storage Mix No.9	220	14.70	24.60	1.66	2.09	1.08	1.50	1.08	FALSE
Ghatghar pumped storage Mix No.10	220	11.20	21.20	1.47	1.95	0.90	1.36	0.90	1.36
Ghatghar pumped storage Mix No.11	220	8.50	18.40	1.30	1.83	0.75	1.25	FALSE	1.25
Ghatghar pumped storage Mix No.12	220	7.10	15.80	1.20	1.71	0.67	1.13	FALSE	FALSE
Ghatghar pumped storage Mix No.13	220	5.10	8.80	1.03	1.32	0.53	0.77	FALSE	FALSE
Ghatghar pumped storage Mix No.14	240	15.00	21.50	1.67	1.96	1.09	1.37	1.09	1.37
Ghatghar pumped storage Mix No.15	240	17.00	22.60	1.77	2.01	1.18	1.42	FALSE	1.42
Ghatghar pumped storage Mix No.16	240	11.60	18.70	1.49	1.85	0.92	1.26	0.92	1.26
Ghatghar pumped storage Mix No.17	240	8.20	11.40	1.28	1.48	0.73	0.91	FALSE	FALSE

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m$^{3)}$	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
New Big Cherry	152		10.34		1.42		0.86	FALSE	FALSE
Elkwater Fork Mix 1	148		10.34		1.42		0.86	FALSE	FALSE
Elkwater Fork Mix 2	184		17.24		1.78		1.19	FALSE	1.19
Tannur Mix 2	170	16.70	19.80	1.76	1.89	1.17	1.30	FALSE	1.30
Sama El-Serhan	181		9.40		1.36		0.80	FALSE	FALSE
Marathia	60	4.14	4.99	0.94	1.02	0.46	0.52	FALSE	FALSE
hgin Stage 1 Mix	195	6.50	11.50	1.15	1.49	0.63	0.92	FALSE	FALSE
Jahgin Stage 2 RCC 1-1 with Khash Natural Pozzolan	225	13.00	19.00	1.57	1.86	1.00	1.27	1.00	1.27
Jahgin Stage 2 RCC 2-1 with Khash Natural Pozzolan	195	16.00	18.00	1.72	1.81	1.14	1.23	FALSE	1.23
Jahgin Stage 2 RCC 1-1 with Low-Lime Flyash	220	9.50	17.00	1.36	1.77	0.81	1.18	FALSE	1.18
Lajeado Mix No.1	70		6.00		1.11		0.59	FALSE	FALSE
Lajeado Mix No.2	100	8.40	11.10	1.29	1.46	0.75	0.90	FALSE	FALSE
Lajeado Mix No.3	120	10.70	14.00	1.44	1.62	0.88	1.04	FALSE	FALSE
Lajeado Mix No.4	140	13.00	16.50	1.57	1.75	1.00	1.16	1.00	FALSE
Lajeado Mix No.5	160	15.90	19.80	1.72	1.89	1.13	1.30	FALSE	1.30
Lajeado Mix No.6	180	24.20	29.00	2.07	2.24	1.48	1.66	FALSE	FALSE
Lajeado Mix No.7	180	24.50	33.00	2.08	2.38	1.49	1.80	FALSE	FALSE
Nunome	120	7.50	14.00	1.23	1.62	0.69	1.04	FALSE	FALSE
Urayama	130		31.00		2.31		1.73	FALSE	FALSE
Hiyoshi	120		27.00		2.17		1.59	FALSE	FALSE
Tomisato No.1	120		23.00		2.02		1.43	FALSE	FALSE
Pedrógão Mix 1	200	15.10		1.68		1.10		1.10	FALSE
Pedrógão Mix 2	200	13.50		1.60		1.02		1.02	FALSE
Pedrógão Mix 3	200							FALSE	FALSE
Pedrógão Mix 4	180	8.00		1.26		0.72		FALSE	FALSE
Pedrógão Mix 5	160	7.80		1.25		0.71		FALSE	FALSE

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Three Gorges Mix.1	198	27.60	36.20	2.20	2.48	1.61	1.90	FALSE	FALSE
Three Gorges Mix.2	196	23.90	31.60	2.06	2.33	1.47	1.75	FALSE	FALSE
Three Gorges Mix.3	193	19.30	23.40	1.87	2.04	1.28	1.45	FALSE	FALSE
Three Gorges Mix.4	178	23.60	32.80	2.05	2.37	1.46	1.79	FALSE	FALSE
Three Gorges Mix.5	176	21.50	28.00	1.96	2.21	1.37	1.62	FALSE	FALSE
Three Gorges Mix.6	174	15.90	22.90	1.72	2.02	1.13	1.43	FALSE	FALSE
Three Gorges Mix.7	162	19.10	28.30	1.86	2.22	1.28	1.63	FALSE	FALSE
Three Gorges Mix.8	160	12.70	23.50	1.55	2.04	0.98	1.45	0.98	FALSE
Three Gorges Mix.9	158	10.10	18.60	1.40	1.84	0.84	1.25	FALSE	1.25
Three Gorges Mix.10	160	29.10	37.00	2.25	2.50	1.66	1.93	FALSE	FALSE
Three Gorges Mix.11	158	25.20	33.00	2.11	2.38	1.52	1.80	FALSE	FALSE
Three Gorges Mix.12	155	21.00	25.00	1.94	2.10	1.35	1.51	FALSE	FALSE
Three Gorges Mix.13	144	24.50	33.40	2.08	2.39	1.49	1.81	FALSE	FALSE
Three Gorges Mix.14	142	21.90	30.10	1.98	2.28	1.39	1.70	FALSE	FALSE
Three Gorges Mix.15	140	15.80	20.20	1.71	1.91	1.13	1.32	FALSE	1.32
Three Gorges Mix.16	131	22.50	28.00	2.00	2.21	1.41	1.62	FALSE	FALSE
Three Gorges Mix.17	130	15.40	24.00	1.69	2.06	1.11	1.47	FALSE	FALSE
Three Gorges Mix.18	127	12.90	20.00	1.56	1.90	0.99	1.31	0.99	1.31
Dona Francisca Mix.1	85	4.70	7.90	1.00	1.26	0.50	0.72	FALSE	FALSE
Dona Francisca Mix.2	85	4.40	8.80	0.97	1.32	0.48	0.77	FALSE	FALSE
Dona Francisca Mix.3	90	4.80	8.60	1.01	1.31	0.51	0.76	FALSE	FALSE
Dona Francisca Mix.4	90	4.80	9.00	1.01	1.33	0.51	0.78	FALSE	FALSE
Dona Francisca Mix.5	100	5.50	11.40	1.07	1.48	0.56	0.91	FALSE	FALSE

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m$^{3)}$	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Dona Francisca Mix.6	90	4.40	7.30	0.97	1.21	0.48	0.68	FALSE	FALSE
Dona Francisca Mix.7	94	4.40	7.50	0.97	1.23	0.48	0.69	FALSE	FALSE
Dona Francisca Mix.8	94	4.50	8.00	0.98	1.26	0.49	0.72	FALSE	FALSE
Dona Francisca Mix.9	94	5.10	8.50	1.03	1.30	0.53	0.75	FALSE	FALSE
Dona Francisca Mix.10	100	5.00	8.80	1.02	1.32	0.52	0.77	FALSE	FALSE
Beni Haroun	225	16.00	24.00	1.72	2.06	1.14	1.47	FALSE	FALSE
Mujib	85	6.82	8.44	1.18	1.29	0.65	0.75	FALSE	FALSE
El Esparragal	225	10.40	17.47	1.42	1.79	0.86	1.20	FALSE	1.20
El Esparragal Mix.1	225	9.19	17.17	1.34	1.78	0.79	1.19	FALSE	1.19
El Esparragal Mix.2	225	14.35	18.42	1.64	1.83	1.06	1.25	1.06	1.25
El Esparragal Mix.3	225	31.93	35.64	2.34	2.46	1.76	1.88	FALSE	FALSE
Olivenhain	195	8.27	15.86	1.28	1.72	0.74	1.13	FALSE	FALSE
Olivenhain Mix.1	195	10.00	14.82	1.40	1.66	0.84	1.08	FALSE	FALSE
Olivenhain Mix.2	195	7.58	12.41	1.23	1.54	0.70	0.97	FALSE	FALSE
Olivenhain Mix.3	195	6.76	12.06	1.17	1.52	0.64	0.95	FALSE	FALSE
Badovli	160	9.00	11.50	1.33	1.49	0.78	0.92	FALSE	FALSE
Son La Stage I Mix 0	225	7.00	14.50	1.19	1.65	0.66	1.07	FALSE	FALSE
Son La Stage I Mix 1	230	8.50	19.70	1.30	1.89	0.75	1.30	FALSE	1.30
Son La Stage I Mix 2	230	13.50	20.00	1.60	1.90	1.02	1.31	1.02	1.31
Son La Stage I Mix 3	230	16.50	25.00	1.75	2.10	1.16	1.51	FALSE	FALSE
Son La Stage I Mix 4	230	21.00	32.00	1.94	2.35	1.35	1.76	FALSE	FALSE
Son La Stage I Mix 5	230	27.00	33.00	2.17	2.38	1.59	1.80	FALSE	FALSE
Son La Stage II Mix 1	200	9.00	14.00	1.33	1.62	0.78	1.04	FALSE	FALSE
Son La Stage II Mix 2	200	11.00	16.00	1.46	1.72	0.89	1.14	FALSE	FALSE
Son La Stage II Mix 3	200	15.00	20.00	1.67	1.90	1.09	1.31	1.09	1.31

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Yeywa Stage I-A Mix 1	210		12.00		1.51		0.94	FALSE	FALSE
Yeywa Stage I-A Mix 2	210	10.00	13.00	1.40	1.57	0.84	1.00	FALSE	FALSE
Yeywa Stage I-A Mix 3	210	11.00	14.00	1.46	1.62	0.89	1.04	FALSE	FALSE
Yeywa Stage I-A Mix 4	210	12.00	15.00	1.51	1.67	0.94	1.09	0.94	FALSE
Yeywa Stage I-A Mix 5	210		17.00		1.77		1.18	FALSE	1.18
Yeywa Stage I-B Mix 1	220	9.50	10.00	1.36	1.40	0.81	0.84	FALSE	FALSE
Yeywa Stage I-B Mix 2	220	12.00	17.00	1.51	1.77	0.94	1.18	0.94	1.18
Yeywa Stage I-B Mix 3	220	14.00		1.62		1.04		1.04	FALSE
Yeywa Stage I-B Mix 4	220	12.50	19.00	1.54	1.86	0.97	1.27	0.97	1.27
Yeywa Stage I-B Mix 5	220	18.00	23.00	1.81	2.02	1.23	1.43	FALSE	FALSE
Yeywa Stage I-B Mix 6	220	21.00	26.00	1.94	2.14	1.35	1.55	FALSE	FALSE
Yeywa Stage II Mix 1	220	11.00		1.46		0.89		FALSE	FALSE
Yeywa Stage II Mix 2	220	11.00	16.00	1.46	1.72	0.89	1.14	FALSE	FALSE
Yeywa Stage II Mix 3	220	13.00	17.00	1.57	1.77	1.00	1.18	1.00	1.18
Yeywa Stage II Mix 4	220	15.00	20.00	1.67	1.90	1.09	1.31	1.09	1.31
Yeywa Stage II Mix 5	220	16.00	21.00	1.72	1.94	1.14	1.35	FALSE	1.35
Camp Dyer	163	10.10		1.40		0.84		FALSE	FALSE
Concepcion	90	5.50	7.60	1.07	1.24	0.56	0.70	FALSE	FALSE
Elk Creek	84	3.00	9.00	0.82	1.33	0.36	0.78	FALSE	FALSE
Middle Fork	66	8.80	11.40	1.32	1.48	0.77	0.91	FALSE	FALSE
Santa Cruz	151	8.90	15.00	1.33	1.67	0.78	1.09	FALSE	FALSE
Stacy - spillway	187	18.10	21.40	1.82	1.96	1.23	1.37	FALSE	1.37
Stagecoach	148	2.40		0.74		0.31		FALSE	FALSE
Urugua-i	60	6.40	8.10	1.14	1.27	0.62	0.73	FALSE	FALSE
Cana Brava	100	7.20	9.40	1.21	1.36	0.67	0.80	FALSE	FALSE
New Big Cherry	152		10.34		1.42		0.86	FALSE	FALSE
Pine Brook	154		10.34		1.42		0.86	FALSE	FALSE
Genesee Dam No.2	169		10.34		1.42		0.86	FALSE	FALSE

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m$^{3)}$	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Hickory Log Creek Mix 2	178		13.79		1.61		1.03	FALSE	FALSE
Elkwater Fork Mix 1	148		10.34		1.42		0.86	FALSE	FALSE
Elkwater Fork Mix 2	184		17.24		1.78		1.19	FALSE	1.19
Tannur Mix 2	170	16.70	19.80	1.76	1.89	1.17	1.30	FALSE	1.30
Sama El-Serhan	181		9.40		1.36		0.80	FALSE	FALSE
Villarpando	90	8.85	11.50	1.32	1.49	0.77	0.92	FALSE	FALSE
Marathia	70	4.14	4.99	0.94	1.02	0.46	0.52	FALSE	FALSE
Jahgin Stage 1 Mix 1	195	6.50	11.50	1.15	1.49	0.63	0.92	FALSE	FALSE
Jahgin Stage 1 Mix 2	195	9.00	12.50	1.33	1.54	0.78	0.97	FALSE	FALSE
Jahgin Stage 1 Mix 3	195	13.00	16.00	1.57	1.72	1.00	1.14	1.00	FALSE
Jahgin Stage 1 Mix 4	195	14.00	20.00	1.62	1.90	1.04	1.31	1.04	1.31
Jahgin Stage 1 Mix 5	195	16.00	20.50	1.72	1.92	1.14	1.33	FALSE	1.33
Jahgin Stage 1 Mix 6	190	18.50	24.00	1.84	2.06	1.25	1.47	FALSE	FALSE
Jahgin Stage 2 RCC 1-1 with Khash Natural Pozzolan	225	13.00	19.00	1.57	1.86	1.00	1.27	1.00	1.27
Jahgin Stage 2 RCC 1-2 with Khash Natural Pozzolan	225	14.00	16.00	1.62	1.72	1.04	1.14	1.04	FALSE
Jahgin Stage 2 RCC 1-3 with Khash Natural Pozzolan	225	8.00	10.00	1.26	1.40	0.72	0.84	FALSE	FALSE
Jahgin Stage 2 RCC 2-1 with Khash Natural Pozzolan	195	7.00	14.00	1.19	1.62	0.66	1.04	FALSE	FALSE
Jahgin Stage 2 RCC 2-2 with Khash Natural Pozzolan	195	7.00	13.50	1.19	1.60	0.66	1.02	FALSE	FALSE
Nunome	120	7.50	14.00	1.23	1.62	0.69	1.04	FALSE	FALSE
Nunome Mix 1	140	12.50	17.50	1.54	1.79	0.97	1.21	0.97	1.21
Nunome Mix 2	140	7.70	15.20	1.24	1.68	0.70	1.10	FALSE	FALSE
Nunome Mix 3	140	7.30	14.20	1.21	1.63	0.68	1.05	FALSE	FALSE

Table A.3 The Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dam Mixes (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength (MPa) for 28 days	Splitting tensile strength (MPa) for 90 days	Direct tensile strength (MPa) for 28 days	Direct tensile strength (MPa) for 90 days	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days
Nunome Mix 4	140	7.30	14.00	1.21	1.62	0.68	1.04	FALSE	FALSE
Urayama	130		31.00		2.31		1.73	FALSE	FALSE
Hiyoshi	120		27.00		2.17		1.59	FALSE	FALSE
Tomisato No.1	120		23.00		2.02		1.43	FALSE	FALSE
Tomisato No.2	120		17.00		1.77		1.18	FALSE	1.18
Cenza	200	19.40	29.00	1.88	2.24	1.29	1.66	FALSE	FALSE
Beni Haroun	225	16.00	24.00	1.72	2.06	1.14	1.47	FALSE	FALSE
Mujib	85	6.82	8.44	1.18	1.29	0.65	0.75	FALSE	FALSE
El Esparragal	225	10.40	17.47	1.42	1.79	0.86	1.20	FALSE	1.20
El Esparragal Mix.1	225	9.19	17.17	1.34	1.78	0.79	1.19	FALSE	1.19
El Esparragal Mix.2	225	14.35	18.42	1.64	1.83	1.06	1.25	1.06	1.25
El Esparragal Mix.3	225	31.93	35.64	2.34	2.46	1.76	1.88	FALSE	FALSE
Porce II	220	16.00	19.80	1.72	1.89	1.14	1.30	FALSE	1.30
Olivenhain	195	8.27	15.86	1.28	1.72	0.74	1.13	FALSE	FALSE
Olivenhain Mix.1	195	10.00	14.82	1.40	1.66	0.84	1.08	FALSE	FALSE
Olivenhain Mix.2	195	7.58	12.41	1.23	1.54	0.70	0.97	FALSE	FALSE
Olivenhain Mix.3	195	6.76	12.06	1.17	1.52	0.64	0.95	FALSE	FALSE
El Zapotillo Mix 1	331	11.00	14.00	1.46	1.62	0.89	1.04	FALSE	FALSE
El Zapotillo Mix 2	350	12.00	16.00	1.51	1.72	0.94	1.14	0.94	FALSE
El Zapotillo Mix 3	368	13.00	17.00	1.57	1.77	1.00	1.18	1.00	1.18
Shapai Mix 1	192	14.00	18.40	1.62	1.83	1.04	1.25	1.04	1.25
Shapai Mix 2	192	13.30	18.00	1.59	1.81	1.01	1.23	1.01	1.23
Linhekou Mix 1	185	18.00	26.70	1.81	2.16	1.23	1.58	FALSE	FALSE
Linhekou Mix 2	172	18.90	25.30	1.85	2.11	1.27	1.52	FALSE	FALSE
Zhaolaihe	210	13.10	29.20	1.57	2.25	1.00	1.67	1.00	FALSE
Zhaolaihe	229	14.50	24.90	1.65	2.10	1.07	1.51	1.07	FALSE
Wenquanbao	195	24.50	29.90	2.08	2.28	1.49	1.69	FALSE	FALSE
Wenquanbao	173	17.70	21.40	1.80	1.96	1.21	1.37	FALSE	1.37
Puding	188	22.20	32.10	1.99	2.35	1.40	1.77	FALSE	FALSE
Bailianya	180	19.70	28.70	1.89	2.23	1.30	1.65	FALSE	FALSE
Badovli	160	9.00	11.50	1.33	1.49	0.78	0.92	FALSE	FALSE
Naras Mix 1	125	10.80	13.90	1.45	1.62	0.88	1.04	FALSE	FALSE
Naras Mix 2	150	15.10	17.90	1.68	1.81	1.10	1.22	1.10	1.22
Naras Mix 3	175	18.00	22.20	1.81	1.99	1.23	1.40	FALSE	1.40
Naras Mix 4	200	21.90	28.60	1.98	2.23	1.39	1.64	FALSE	FALSE
Silopi Mix 4	100	11.53	13.04	1.49	1.57	0.92	1.00	0.92	FALSE
Silopi Mix 1	120	15.55	17.19	1.70	1.78	1.12	1.19	FALSE	1.19
Silopi Mix 2	140	20.19	24.46	1.91	2.08	1.32	1.49	FALSE	FALSE
Silopi Mix 3	160	26.46	31.54	2.15	2.33	1.57	1.75	FALSE	FALSE
			Mean	**1.53**	**1.80**	**0.97**	**1.22**	**1.02**	**1.28**

Table A.4 The Correlations Between Compressive, Splitting Tensile and Direct Tensile Strength Values of RCC Dams Trial Mixes

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Splitting tensile strength / Compresssive strength ratio for 28 days	Splitting tensile strength / Compresssive strength ratio for 90 days	Direct tensile strength / Splitting tensile strength ratio for 28 days	Direct tensile strength / Splitting tensile strength ratio for 90 days
Upper Stillwater Mix 3	233	12.60	17.90	0.12	0.10	0.63	0.68
Willow Creek Mix 1	104	12.80	18.30	0.12	0.10	0.63	0.68
Ghatghar pumped storage Mix No.5	200	14.40	21.20	0.11	0.09	0.65	0.70
Ghatghar pumped storage Mix No.14	240	15.00	21.50	0.11	0.09	0.65	0.70
Sa Stria Mix.5	212	12.30	19.90	0.12	0.10	0.63	0.69
Sa Stria Mix.6	223	14.10	21.40	0.12	0.09	0.64	0.70
Nordlingaalda Mix.2	105	15.00	22.00	0.11	0.09	0.65	0.70
Ghatghar pumped storage Mix No.6	200	11.90	19.50	0.13	0.10	0.62	0.69
Ghatghar pumped storage Mix No.10	220	11.20	21.20	0.13	0.09	0.61	0.70
Ghatghar pumped storage Mix No.14	240	15.00	21.50	0.11	0.09	0.65	0.70
Three Gorges Mix.18	127	12.90	20.00	0.12	0.10	0.63	0.69
El Esparragal Mix.2	225	14.35	18.42	0.11	0.10	0.65	0.68
Son La Stage I Mix 2	230	13.50	20.00	0.12	0.10	0.64	0.69
Son La Stage II Mix 3	200	15.00	20.00	0.11	0.10	0.65	0.69
Yeywa Stage I-B Mix 4	220	12.50	19.00	0.12	0.10	0.63	0.68
Yeywa Stage II Mix 3	220	13.00	17.00	0.12	0.10	0.63	0.67
Yeywa Stage II Mix 4	220	15.00	20.00	0.11	0.10	0.65	0.69
Nunome Mix 1	140	12.50	17.50	0.12	0.10	0.63	0.67
Shapai Mix 1	192	14.00	18.40	0.12	0.10	0.64	0.68
Shapai Mix 2	192	13.30	18.00	0.12	0.10	0.64	0.68
Naras Mix 2	150	15.10	17.90	0.11	0.10	0.65	0.68
			Mean	**0.13**	**0.11**	**0.62**	**0.67**

Table A.5 The Cost Analysis for RCC Mix Design

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Pozzolan / Cementitious content Ratio	1.00 MPa Target Direct Tensile Strength for 28 days	1.30 MPa Target Direct Tensile Strength for 90 days	Cost of Cement (TL*(kg/m^3))	Cost of Pozzolan (TL*(kg/m^3))	Total Cost (TL*(kg/m^3))
Upper Stillwater Mix 3	233	108	125	0.54	0.98	1.22	11.77	2.11	13.88
Willow Creek Mix 1	104	104	0	0.00	0.99	1.24	11.34	0.00	11.34
Ghatghar pumped storage Mix No.5	200	120	80	0.40	1.06	1.36	13.08	1.35	14.43
Ghatghar pumped storage Mix No.6	200	100	100	0.50	0.94	1.29	10.90	1.69	12.59
Ghatghar pumped storage Mix No.10	220	132	88	0.40	0.90	1.36	14.39	1.49	15.88
Ghatghar pumped storage Mix No.14	240	144	96	0.40	1.09	1.37	15.70	1.62	17.32
Ghatghar pumped storage Mix No.16	240	96	144	0.60	0.92	1.26	10.46	2.43	12.90
Sa Stria Mix.5	212	75	137	0.65	0.96	1.31	8.18	2.32	10.49
Sa Stria Mix.6	223	92	131	0.59	1.05	1.37	10.03	2.21	12.24
Nordlingaalda Mix.2	105	105	0	0.00	1.09	1.39	11.45	0.00	11.45
Three Gorges Mix.18	127	51	76	0.60	0.99	1.31	5.56	1.28	6.84
El Esparragal Mix.2	225	79	146	0.65	1.06	1.25	8.61	2.47	11.08
Son La Stage I Mix 2	230	85	145	0.63	1.02	1.31	9.27	2.45	11.72
Son La Stage II Mix 3	200	75	125	0.63	1.09	1.31	8.18	2.11	10.29
Yeywa Stage I-B Mix 4	220	60	160	0.73	0.97	1.27	6.54	2.70	9.24
Yeywa Stage II Mix 3	220	66	154	0.70	1.00	1.18	7.19	2.60	9.80
Yeywa Stage II Mix 4	220	70.4	149.6	0.68	1.09	1.31	7.67	2.53	10.20
Nunome Mix 1	140	140	0	0.00	0.97	1.21	15.26	0.00	15.26
Shapai Mix 1	192	115	77	0.40	1.04	1.25	12.54	1.30	13.84
Shapai Mix 2	192	96	96	0.50	1.01	1.23	10.46	1.62	12.09
Naras Mix 2	150	150	0	0.00	1.10	1.22	16.35	0.00	16.35
				Mean	**1.02**	**1.29**			

APPENDIX B

TABLES OF MECHANICAL PROPERTIES OF RCC DAMS

Table B.1 Compressive Strength vs. Cementitious Content for RCC Dams

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Galesville Mix 1	104	4.00	7.00
Galesville Mix 2	133	5.70	9.40
Zintel Canyon Mix 1	178	11.20	14.70
Zintel Canyon Mix 2	74	4.30	7.50
Upper Stillwater Mix 1	301	17.70	24.80
Upper Stillwater Mix 2	299	23.60	29.00
Upper Stillwater Mix 3	233	12.60	17.90
Upper Stillwater Mix 4	252	15.40	21.40
Upper Stillwater Mix 5	252	14.70	24.20
Upper Stillwater Mix 6	232	8.40	14.80
Willow Creek Mix 1	104	12.80	18.30
Willow Creek Mix 2	151	14.20	27.30
Willow Creek Mix 3	267	23.50	30.80
Willow Creek Mix 4	66	8.10	11.90

Table B.1 Compressive Strength vs. Cementitious Content for RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/ m3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Ghatghar pumped storage Mix No.1	180	11.00	14.10
Ghatghar pumped storage Mix No.5	200	14.40	21.20
Ghatghar pumped storage Mix No.9	220	14.70	24.60
Ghatghar pumped storage Mix No.14	240	15.00	21.50
Miel I Mix.1	150		17.00
Miel I Mix.2	125		13.50
Miel I Mix.3	100		9.50
Miel I Mix.4	85		8.00
Saluda dam remediation primary	163	4.31	7.76
Saluda dam remediation Mix 2	178	7.24	12.41
Lajeado Mix No.2	100	8.40	11.10
Lajeado Mix No.4	140	13.00	16.50
Pedrógão Mix 1	200	15.10	
Pedrógão Mix 4	180	8.00	
Pedrógão Mix 5	160	7.80	
Capanda Mix. 1	80	8.40	10.00
Capanda Mix. 2	70	7.60	9.80
Three Gorges Mix.1	198	27.60	36.20
Three Gorges Mix.4	178	23.60	32.80
Dona Francisca Mix.1	85	4.70	7.90
Dona Francisca Mix.3	90	4.80	8.60

Table B.1 Compressive Strength vs. Cementitious Content for RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Sa Stria Mix.5	212	12.30	19.90
Sa Stria Mix.6	223	14.10	21.40
Nordlingaalda Mix.1	80	9.20	15.00
Nordlingaalda Mix.2	105	15.00	22.00
Nordlingaalda Mix.3	133	22.50	31.00
Nordlingaalda Mix.4	213	45.50	57.50
Longtan Trial Mix 1	191	27.30	42.60
Longtan Trial Mix 3	160	16.40	26.40
Longshou Mix 1	205	25.80	34.40
Longshou Mix 2	171	20.80	27.50
Camp Dyer	163	10.10	
Concepcion	90	5.50	7.60
Elk Creek	84	3.00	9.00
Middle Fork	66	8.80	11.40
Santa Cruz	151	8.90	15.00
Stacy - spillway	187	18.10	21.40
Stagecoach	148	2.40	
Urugua-i	60	6.40	8.10
Cana Brava	100	7.20	9.40
New Big Cherry	152		10.34
Pine Brook	154		10.34
Genesee Dam No.2	169		10.34
Hickory Log Creek Mix 2	178		13.79
Elkwater Fork Mix 1	148		10.34
Elkwater Fork Mix 2	184		17.24

Table B.1 Compressive Strength vs. Cementitious Content for RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/ m3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Tannur Mix 2	170	16.70	19.80
Sama El-Serhan	181		9.40
Villarpando	90	8.85	11.50
Marathia	70	4.14	4.99
Jahgin Stage 1 Mix 1	195	6.50	11.50
Jahgin Stage 1 Mix 2	195	9.00	12.50
Jahgin Stage 1 Mix 3	195	13.00	16.00
Jahgin Stage 1 Mix 4	195	14.00	20.00
Jahgin Stage 1 Mix 5	195	16.00	20.50
Jahgin Stage 1 Mix 6	190	18.50	24.00
Jahgin Stage 2 RCC 1-1 with Khash Natural Pozzolan	225	13.00	19.00
Jahgin Stage 2 RCC 1-2 with Khash Natural Pozzolan	225	14.00	16.00
Jahgin Stage 2 RCC 1-3 with Khash Natural Pozzolan	225	8.00	10.00
Jahgin Stage 2 RCC 2-1 with Khash Natural Pozzolan	195	7.00	14.00
Jahgin Stage 2 RCC 2-2 with Khash Natural Pozzolan	195	7.00	13.50

Table B.1 Compressive Strength vs. Cementitious Content for RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Nunome	120	7.50	14.00
Nunome Mix 1	140	12.50	17.50
Nunome Mix 2	140	7.70	15.20
Nunome Mix 3	140	7.30	14.20
Nunome Mix 4	140	7.30	14.00
Urayama	130		31.00
Hiyoshi	120		27.00
Tomisato No.1	120		23.00
Tomisato No.2	120		17.00
Cenza	200	19.40	29.00
Beni Haroun	225	16.00	24.00
Mujib	85	6.82	8.44
El Esparragal	225	10.40	17.47
El Esparragal Mix.1	225	9.19	17.17
El Esparragal Mix.2	225	14.35	18.42
El Esparragal Mix.3	225	31.93	35.64
Porce II	220	16.00	19.80
Olivenhain	195	8.27	15.86
Olivenhain Mix.1	195	10.00	14.82
Olivenhain Mix.2	195	7.58	12.41
Olivenhain Mix.3	195	6.76	12.06
Son La Stage II Mix 2 with Reduced Carbon Flyash	200	9.00	16.50
Son La Stage II Mix 3 with Reduced Carbon Flyash	200	11.00	18.00

Table B.1 Compressive Strength vs. Cementitious Content for RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Son La Stage I Mix 0	225	7.00	14.50
Son La Stage I Mix 1	230	8.50	19.70
Son La Stage I Mix 2	230	13.50	20.00
Son La Stage I Mix 3	230	16.50	25.00
Son La Stage I Mix 4	230	21.00	32.00
Son La Stage I Mix 5	230	27.00	33.00
Yeywa Stage I-A Mix 1	210		12.00
Yeywa Stage I-A Mix 2	210	10.00	13.00
Yeywa Stage I-A Mix 3	210	11.00	14.00
Yeywa Stage I-A Mix 4	210	12.00	15.00
Yeywa Stage I-A Mix 5	210		17.00
Yeywa Stage I-B Mix 1	210	9.50	10.00
Yeywa Stage I-B Mix 2	220	12.00	17.00
Yeywa Stage I-B Mix 3	220	14.00	
Yeywa Stage I-B Mix 4	220	12.50	19.00
Yeywa Stage I-B Mix 5	220	18.00	23.00
Yeywa Stage I-B Mix 6	220	21.00	26.00

Table B.1 Compressive Strength vs. Cementitious Content for RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Yeywa Stage II Mix 1	220	11.00	
Yeywa Stage II Mix 2	220	11.00	16.00
Yeywa Stage II Mix 3	220	13.00	17.00
Yeywa Stage II Mix 4	220	15.00	20.00
Yeywa Stage II Mix 5	220	16.00	21.00
El Zapotillo Mix 1	331	11.00	14.00
El Zapotillo Mix 2	350	12.00	16.00
El Zapotillo Mix 3	368	13.00	17.00
Shapai Mix 1	192	14.00	18.40
Shapai Mix 2	192	13.30	18.00
Linhekou Mix 1	185	18.00	26.70
Linhekou Mix 2	172	18.90	25.30
Zhaolaihe Mix 1	210	13.10	29.20
Zhaolaihe Mix 2	229	14.50	24.90
Wenquanbao Mix 1	195	24.50	29.90
Wenquanbao Mix 2	173	17.70	21.40
Puding	188	22.20	32.10
Bailianya	180	19.70	28.70
Badovli	160	9.00	11.50
Naras Mix 1	125	10.80	13.90
Naras Mix 2	150	15.10	17.90
Naras Mix 3	175	18.00	22.20
Naras Mix 4	200	21.90	28.60
Silopi Mix 4	100	11.53	13.04
Silopi Mix 1	120	15.55	17.19
Silopi Mix 2	140	20.19	24.46
Silopi Mix 3	160	26.46	31.54

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Galesville Mix 1	104	4.00	7.00	0.04	0.07
Galesville Mix 2	133	5.70	9.40	0.04	0.07
Zintel Canyon Mix 1	178	11.20	14.70	0.06	0.08
Zintel Canyon Mix 2	74	4.30	7.50	0.06	0.10
Upper Stillwater Mix 1	301	17.70	24.80	0.06	0.08
Upper Stillwater Mix 2	299	23.60	29.00	0.08	0.10
Upper Stillwater Mix 3	233	12.60	17.90	0.05	0.08
Upper Stillwater Mix 4	252	15.40	21.40	0.06	0.08
Upper Stillwater Mix 5	252	14.70	24.20	0.06	0.10
Upper Stillwater Mix 6	232	8.40	14.80	0.04	0.06
Willow Creek Mix 1	104	12.80	18.30	0.12	0.18
Willow Creek Mix 2	151	14.20	27.30	0.09	0.18
Willow Creek Mix 3	267	23.50	30.80	0.09	0.12
Willow Creek Mix 4	66	8.10	11.90	0.12	0.18
Ghatghar pumped storage Mix No.1	180	11.00	14.10	0.06	0.08
Ghatghar pumped storage Mix No.5	200	14.40	21.20	0.07	0.11
Ghatghar pumped storage Mix No.9	220	14.70	24.60	0.07	0.11
Ghatghar pumped storage Mix No.14	240	15.00	21.50	0.06	0.09
Miel I Mix.1	150		17.00		0.11
Miel I Mix.2	125		13.50		0.11
Miel I Mix.3	100		9.50		0.10
Miel I Mix.4	85		8.00		0.09
Saluda dam remediation primary	163	4.31	7.76	0.03	0.05
Saluda dam remediation Mix 2	178	7.24	12.41	0.04	0.07
Lajeado Mix No.2	100	8.40	11.10	0.08	0.11
Lajeado Mix No.4	140	13.00	16.50	0.09	0.12
Pedrógão Mix 1	200	15.10		0.08	
Pedrógão Mix 4	180	8.00		0.04	
Pedrógão Mix 5	160	7.80		0.05	
Capanda Mix. 1	80	8.40	10.00	0.11	0.13
Capanda Mix. 2	70	7.60	9.80	0.11	0.14
Three Gorges Mix.1	198	27.60	36.20	0.14	0.18
Three Gorges Mix.4	178	23.60	32.80	0.13	0.18
Dona Francisca Mix.1	85	4.70	7.90	0.06	0.09
Dona Francisca Mix.3	90	4.80	8.60	0.05	0.10
Sa Stria Mix.5	212	12.30	19.90	0.06	0.09
Sa Stria Mix.6	223	14.10	21.40	0.06	0.10

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m³)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Nordlingaalda Mix.1	80	9.20	15.00	0.12	0.19
Nordlingaalda Mix.2	105	15.00	22.00	0.14	0.21
Nordlingaalda Mix.3	133	22.50	31.00	0.17	0.23
Nordlingaalda Mix.4	213	45.50	57.50	0.21	0.27
Longtan Trial Mix 1	191	27.30	42.60	0.14	0.22
Longtan Trial Mix 3	160	16.40	26.40	0.10	0.17
Longshou Mix 1	205	25.80	34.40	0.13	0.17
Longshou Mix 2	171	20.80	27.50	0.12	0.16
Camp Dyer	163	10.10		0.06	
Middle Fork	66	8.80	11.40	0.13	0.17
Stacy Spillway	187	18.10	21.40	0.10	0.11
Upper Stillwater Mix 1	301	17.70	24.80	0.06	0.08
Upper Stillwater Mix 2	299	23.60	29.00	0.08	0.10
Upper Stillwater Mix 3	252	14.70	24.20	0.06	0.10
Upper Stillwater Mix 4	252	15.40	21.40	0.06	0.08
Upper Stillwater Mix 5	233	12.60	17.90	0.05	0.08
Upper Stillwater Mix 6	232	8.40	14.80	0.04	0.06
Ghatghar pumped storage Mix No.1	180	11.00	14.10	0.06	0.08
Ghatghar pumped storage Mix No.2	180	9.60	13.00	0.05	0.07
Ghatghar pumped storage Mix No.3	180	9.00	12.70	0.05	0.07
Ghatghar pumped storage Mix No.4	180	6.80	10.50	0.04	0.06
Ghatghar pumped storage Mix No.5	200	14.40	21.20	0.07	0.11
Ghatghar pumped storage Mix No.6	200	11.90	19.50	0.06	0.10
Ghatghar pumped storage Mix No.7	200	9.30	15.00	0.05	0.08
Ghatghar pumped storage Mix No.8	200	7.30	12.40	0.04	0.06
Ghatghar pumped storage Mix No.9	220	14.70	24.60	0.07	0.11
Ghatghar pumped storage Mix No.10	220	11.20	21.20	0.05	0.10
Ghatghar pumped storage Mix No.11	220	8.50	18.40	0.04	0.08
Ghatghar pumped storage Mix No.12	220	7.10	15.80	0.03	0.07
Ghatghar pumped storage Mix No.13	220	5.10	8.80	0.02	0.04

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Ghatghar pumped storage Mix No.14	240	15.00	21.50	0.06	0.09
Ghatghar pumped storage Mix No.15	240	17.00	22.60	0.07	0.09
Ghatghar pumped storage Mix No.16	240	11.60	18.70	0.05	0.08
Ghatghar pumped storage Mix No.17	240	8.20	11.40	0.03	0.05
New Big Cherry	152		10.34		0.07
Elkwater Fork Mix 1	148		10.34		0.07
Elkwater Fork Mix 2	184		17.24		0.09
Tannur Mix 2	170	16.70	19.80	0.10	0.12
Sama El-Serhan	181		9.40		0.05
Marathia	60	4.14	4.99	0.07	0.08
Jahgin Stage 1 Mix 1	195	6.50	11.50	0.03	0.06
Jahgin Stage 2 RCC 1-1 with Khash Natural Pozzolan	225	13.00	19.00	0.06	0.08
Jahgin Stage 2 RCC 2-1 with Khash Natural Pozzolan	195	16.00	18.00	0.08	0.09
Jahgin Stage 2 RCC 1-1 with Low-Lime Flyash	220	9.50	17.00	0.04	0.08
Lajeado Mix No.1	70		6.00		0.09
Lajeado Mix No.2	100	8.40	11.10	0.08	0.11
Lajeado Mix No.3	120	10.70	14.00	0.09	0.12
Lajeado Mix No.4	140	13.00	16.50	0.09	0.12
Lajeado Mix No.5	160	15.90	19.80	0.10	0.12
Lajeado Mix No.6	180	24.20	29.00	0.13	0.16
Lajeado Mix No.7	180	24.50	33.00	0.14	0.18
Nunome	120	7.50	14.00	0.06	0.12
Urayama	130		31.00		0.24
Hiyoshi	120		27.00		0.23
Tomisato No.1	120		23.00		0.19
Pedrógão Mix 1	200	15.10		0.08	
Pedrógão Mix 2	200	13.50		0.07	
Pedrógão Mix 3	200				
Pedrógão Mix 4	180	8.00		0.04	
Pedrógão Mix 5	160	7.80		0.05	
Three Gorges Mix.1	198	27.60	36.20	0.14	0.18
Three Gorges Mix.2	196	23.90	31.60	0.12	0.16
Three Gorges Mix.3	193	19.30	23.40	0.10	0.12
Three Gorges Mix.4	178	23.60	32.80	0.13	0.18
Three Gorges Mix.5	176	21.50	28.00	0.12	0.16

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Three Gorges Mix.6	174	15.90	22.90	0.09	0.13
Three Gorges Mix.7	162	19.10	28.30	0.12	0.17
Three Gorges Mix.8	160	12.70	23.50	0.08	0.15
Three Gorges Mix.9	158	10.10	18.60	0.06	0.12
Three Gorges Mix.10	160	29.10	37.00	0.18	0.23
Three Gorges Mix.11	158	25.20	33.00	0.16	0.21
Three Gorges Mix.12	155	21.00	25.00	0.14	0.16
Three Gorges Mix.13	144	24.50	33.40	0.17	0.23
Three Gorges Mix.14	142	21.90	30.10	0.15	0.21
Three Gorges Mix.15	140	15.80	20.20	0.11	0.14
Three Gorges Mix.16	131	22.50	28.00	0.17	0.21
Three Gorges Mix.17	130	15.40	24.00	0.12	0.18
Three Gorges Mix.18	127	12.90	20.00	0.10	0.16
Dona Francisca Mix.1	85	4.70	7.90	0.06	0.09
Dona Francisca Mix.2	85	4.40	8.80	0.05	0.10
Dona Francisca Mix.3	90	4.80	8.60	0.05	0.10
Dona Francisca Mix.4	90	4.80	9.00	0.05	0.10
Dona Francisca Mix.5	100	5.50	11.40	0.06	0.11
Dona Francisca Mix.6	90	4.40	7.30	0.05	0.08
Dona Francisca Mix.7	94	4.40	7.50	0.05	0.08
Dona Francisca Mix.8	94	4.50	8.00	0.05	0.09
Dona Francisca Mix.9	94	5.10	8.50	0.05	0.09
Dona Francisca Mix.10	100	5.00	8.80	0.05	0.09
Beni Haroun	225	16.00	24.00	0.07	0.11
Mujib	85	6.82	8.44	0.08	0.10
El Esparragal	225	10.40	17.47	0.05	0.08
El Esparragal Mix.1	225	9.19	17.17	0.04	0.08
El Esparragal Mix.2	225	14.35	18.42	0.06	0.08
El Esparragal Mix.3	225	31.93	35.64	0.14	0.16
Olivenhain	195	8.27	15.86	0.04	0.08
Olivenhain Mix.1	195	10.00	14.82	0.05	0.08
Olivenhain Mix.2	195	7.58	12.41	0.04	0.06
Olivenhain Mix.3	195	6.76	12.06	0.03	0.06
Badovli	160	9.00	11.50	0.06	0.07
Son La Stage I Mix 0	225	7.00	14.50	0.03	0.06
Son La Stage I Mix 1	230	8.50	19.70	0.04	0.09
Son La Stage I Mix 2	230	13.50	20.00	0.06	0.09
Son La Stage I Mix 3	230	16.50	25.00	0.07	0.11
Son La Stage I Mix 4	230	21.00	32.00	0.09	0.14
Son La Stage I Mix 5	230	27.00	33.00	0.12	0.14
Son La Stage II Mix 1	200	9.00	14.00	0.05	0.07
Son La Stage II Mix 2	200	11.00	16.00	0.06	0.08
Son La Stage II Mix 3	200	15.00	20.00	0.08	0.10

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Yeywa Stage I-A Mix 1	210		12.00		0.06
Yeywa Stage I-A Mix 2	210	10.00	13.00	0.05	0.06
Yeywa Stage I-A Mix 3	210	11.00	14.00	0.05	0.07
Yeywa Stage I-A Mix 4	210	12.00	15.00	0.06	0.07
Yeywa Stage I-A Mix 5	210		17.00		0.08
Yeywa Stage I-B Mix 1	220	9.50	10.00	0.04	0.05
Yeywa Stage I-B Mix 2	220	12.00	17.00	0.05	0.08
Yeywa Stage I-B Mix 3	220	14.00		0.06	
Yeywa Stage I-B Mix 4	220	12.50	19.00	0.06	0.09
Yeywa Stage I-B Mix 5	220	18.00	23.00	0.08	0.10
Yeywa Stage I-B Mix 6	220	21.00	26.00	0.10	0.12
Yeywa Stage II Mix 1	220	11.00		0.05	
Yeywa Stage II Mix 2	220	11.00	16.00	0.05	0.07
Yeywa Stage II Mix 3	220	13.00	17.00	0.06	0.08
Yeywa Stage II Mix 4	220	15.00	20.00	0.07	0.09
Yeywa Stage II Mix 5	220	16.00	21.00	0.07	0.10
Camp Dyer	163	10.10		0.06	
Concepcion	90	5.50	7.60	0.06	0.08
Elk Creek	84	3.00	9.00	0.04	0.11
Middle Fork	66	8.80	11.40	0.13	0.17
Santa Cruz	151	8.90	15.00	0.06	0.10
Stacy - spillway	187	18.10	21.40	0.10	0.11
Stagecoach	148	2.40		0.02	
Urugua-i	60	6.40	8.10	0.11	0.14
Cana Brava	100	7.20	9.40	0.07	0.09
New Big Cherry	152		10.34		0.07
Pine Brook	154		10.34		0.07
Genesee Dam No.2	169		10.34		0.06
Hickory Log Creek Mix 2	178		13.79		0.08
Elkwater Fork Mix 1	148		10.34		0.07
Elkwater Fork Mix 2	184		17.24		0.09
Tannur Mix 2	170	16.70	19.80	0.10	0.12
Sama El-Serhan	181		9.40		0.05
Villarpando	90	8.85	11.50	0.10	0.13

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Yeywa Stage I-A Mix 1	210		12.00		0.06
Yeywa Stage I-A Mix 2	210	10.00	13.00	0.05	0.06
Yeywa Stage I-A Mix 3	210	11.00	14.00	0.05	0.07
Yeywa Stage I-A Mix 4	210	12.00	15.00	0.06	0.07
Yeywa Stage I-A Mix 5	210		17.00		0.08
Yeywa Stage I-B Mix 1	220	9.50	10.00	0.04	0.05
Yeywa Stage I-B Mix 2	220	12.00	17.00	0.05	0.08
Yeywa Stage I-B Mix 3	220	14.00		0.06	
Yeywa Stage I-B Mix 4	220	12.50	19.00	0.06	0.09
Yeywa Stage I-B Mix 5	220	18.00	23.00	0.08	0.10
Yeywa Stage I-B Mix 6	220	21.00	26.00	0.10	0.12
Yeywa Stage II Mix 1	220	11.00		0.05	
Yeywa Stage II Mix 2	220	11.00	16.00	0.05	0.07
Yeywa Stage II Mix 3	220	13.00	17.00	0.06	0.08
Yeywa Stage II Mix 4	220	15.00	20.00	0.07	0.09
Yeywa Stage II Mix 5	220	16.00	21.00	0.07	0.10
Camp Dyer	163	10.10		0.06	
Concepcion	90	5.50	7.60	0.06	0.08
Elk Creek	84	3.00	9.00	0.04	0.11
Middle Fork	66	8.80	11.40	0.13	0.17
Santa Cruz	151	8.90	15.00	0.06	0.10
Stacy - spillway	187	18.10	21.40	0.10	0.11
Stagecoach	148	2.40		0.02	
Urugua-i	60	6.40	8.10	0.11	0.14
Cana Brava	100	7.20	9.40	0.07	0.09
New Big Cherry	152		10.34		0.07
Pine Brook	154		10.34		0.07
Genesee Dam No.2	169		10.34		0.06
Hickory Log Creek Mix 2	178		13.79		0.08
Elkwater Fork Mix 1	148		10.34		0.07
Elkwater Fork Mix 2	184		17.24		0.09
Tannur Mix 2	170	16.70	19.80	0.10	0.12
Sama El-Serhan	181		9.40		0.05
Villarpando	90	8.85	11.50	0.10	0.13
Marathia	70	4.14	4.99	0.06	0.07
Jahgin Stage 1 Mix 1	195	6.50	11.50	0.03	0.06
Jahgin Stage 1 Mix 2	195	9.00	12.50	0.05	0.06
Jahgin Stage 1 Mix 3	195	13.00	16.00	0.07	0.08
Jahgin Stage 1 Mix 4	195	14.00	20.00	0.07	0.10
Jahgin Stage 1 Mix 5	195	16.00	20.50	0.08	0.11
Jahgin Stage 1 Mix 6	190	18.50	24.00	0.10	0.13

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Jahgin Stage 2 RCC 1-1 with Khash Natural Pozzolan	225	13.00	19.00	0.06	0.08
Jahgin Stage 2 RCC 1-2 with Khash Natural Pozzolan	225	14.00	16.00	0.06	0.07
Jahgin Stage 2 RCC 1-3 with Khash Natural Pozzolan	225	8.00	10.00	0.04	0.04
Jahgin Stage 2 RCC 2-1 with Khash Natural Pozzolan	195	7.00	14.00	0.04	0.07
Jahgin Stage 2 RCC 2-2 with Khash Natural Pozzolan	195	7.00	13.50	0.04	0.07
Nunome	120	7.50	14.00	0.06	0.12
Nunome Mix 1	140	12.50	17.50	0.09	0.13
Nunome Mix 2	140	7.70	15.20	0.06	0.11
Nunome Mix 3	140	7.30	14.20	0.05	0.10
Nunome Mix 4	140	7.30	14.00	0.05	0.10
Urayama	130		31.00		0.24
Hiyoshi	120		27.00		0.23
Tomisato No.1	120		23.00		0.19
Tomisato No.2	120		17.00		0.14
Cenza	200	19.40	29.00	0.10	0.15
Beni Haroun	225	16.00	24.00	0.07	0.11
Mujib	85	6.82	8.44	0.08	0.10
El Esparragal	225	10.40	17.47	0.05	0.08
El Esparragal Mix.1	225	9.19	17.17	0.04	0.08
El Esparragal Mix.2	225	14.35	18.42	0.06	0.08
El Esparragal Mix.3	225	31.93	35.64	0.14	0.16
Porce II	220	16.00	19.80	0.07	0.09

Table B.2 Compressive Strength Efficiency vs. Cementitious Content of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^3)	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days
Olivenhain	195	8.27	15.86	0.04	0.08
Olivenhain Mix.1	195	10.00	14.82	0.05	0.08
Olivenhain Mix.2	195	7.58	12.41	0.04	0.06
Olivenhain Mix.3	195	6.76	12.06	0.03	0.06
El Zapotillo Mix 1	331	11.00	14.00	0.03	0.04
El Zapotillo Mix 2	350	12.00	16.00	0.03	0.05
El Zapotillo Mix 3	368	13.00	17.00	0.04	0.05
Shapai Mix 1	192	14.00	18.40	0.07	0.10
Shapai Mix 2	192	13.30	18.00	0.07	0.09
Linhekou Mix 1	185	18.00	26.70	0.10	0.14
Linhekou Mix 2	172	18.90	25.30	0.11	0.15
Zhaolaihe	210	13.10	29.20	0.06	0.14
Zhaolaihe	229	14.50	24.90	0.06	0.11
Wenquanbao	195	24.50	29.90	0.13	0.15
Wenquanbao	173	17.70	21.40	0.10	0.12
Puding	188	22.20	32.10	0.12	0.17
Bailianya	180	19.70	28.70	0.11	0.16
Badovli	160	9.00	11.50	0.06	0.07
Naras Mix 1	125	10.80	13.90	0.09	0.11
Naras Mix 2	150	15.10	17.90	0.10	0.12
Naras Mix 3	175	18.00	22.20	0.10	0.13
Naras Mix 4	200	21.90	28.60	0.11	0.14
Silopi Mix 4	100	11.53	13.04	0.12	0.13
Silopi Mix 1	120	15.55	17.19	0.13	0.14
Silopi Mix 2	140	20.19	24.46	0.14	0.17
Silopi Mix 3	160	26.46	31.54	0.17	0.20

Table B.3 Compressive Strength vs. W/C Ratio of RCC Dams

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^3)	Water content (kg/m^3)	Water/Cementitious (w/c) Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Galesville Mix 1	104	113	1.09	4.00	7.00
Galesville Mix 2	133	113	0.85	5.70	9.40
Zintel Canyon Mix 1	178	101	0.57	11.20	14.70
Zintel Canyon Mix 2	74	101	1.36	4.30	7.50
Upper Stillwater Mix 1	301	89	0.30	17.70	24.80
Upper Stillwater Mix 2	299	100	0.33	23.60	29.00
Upper Stillwater Mix 3	233	99	0.42	12.60	17.90
Upper Stillwater Mix 4	252	94	0.37	15.40	21.40
Willow Creek Mix 1	104	110	1.06	12.80	18.30
Willow Creek Mix 2	151	110	0.73	14.20	27.30
Willow Creek Mix 3	267	109	0.41	23.50	30.80
Willow Creek Mix 4	66	107	1.62	8.10	11.90
Ghatghar pumped storage Mix No.1	180	117	0.65	11.00	14.10
Ghatghar pumped storage Mix No.5	200	116	0.58	14.40	21.20
Ghatghar pumped storage Mix No.9	220	115	0.52	14.70	24.60
Ghatghar pumped storage Mix No.14	240	114	0.48	15.00	21.50
Elkwater Fork Mix 1	148	103	0.70		10.34
Elkwater Fork Mix 2	184	103	0.56		17.24
Saluda dam remediation primary	163	149	0.91	4.31	7.76
Saluda dam remediation Mix 2	178	154	0.87	7.24	12.41

Table B.3 Compressive Strength vs. W/C Ratio of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Water content (kg/m^3)	Water/Cementitious (w/c) Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Pedrógão Mix 1	200	120	0.60	15.10	
Pedrógão Mix 4	180	130	0.72	8.00	
Pedrógão Mix 5	160	120	0.75	7.80	
Capanda Mix. 1	80	102	1.28	8.40	10.00
Capanda Mix. 2	70	102	1.46	7.60	9.80
Dona Francisca Mix.1	85	140	1.65	4.70	7.90
Dona Francisca Mix.2	85	135	1.59	4.40	8.80
Olivenhain	195	124	0.64	8.27	15.86
Olivenhain Mix.1	195	118	0.61	10.00	14.82
Olivenhain Mix.2	195	123	0.63	7.58	12.41
Olivenhain Mix.3	195	132	0.68	6.76	12.06
Nordlingaalda Mix.1	80	134	1.68	9.20	15.00
Nordlingaalda Mix.2	105	136	1.30	15.00	22.00
Nordlingaalda Mix.3	133	135	1.02	22.50	31.00
Nordlingaalda Mix.4	213	138	0.65	45.50	57.50
El Zapotillo Mix 1	331	86	0.26	11.00	14.00
El Zapotillo Mix 2	350	87	0.25	12.00	16.00
El Zapotillo Mix 3	368	87	0.24	13.00	17.00
Beni Haroun	225	101	0.45	16.00	24.00
Capanda Mix. 1	80	102	1.28	8.40	10.00
Capanda Mix. 2	70	102	1.46	7.60	9.80
Capanda Mix. 3	80	115	1.44	8.00	9.50
Capanda Mix. 4	70	120	1.71	5.40	7.60
Capanda Mix. 5	75	120	1.60	6.80	8.60
Urugua-i	60	100	1.67	6.40	8.10
Lajeado Mix No.1	70	135	1.93		6.00
Lajeado Mix No.2	100	140	1.40	8.40	11.10
Lajeado Mix No.3	120	146	1.22	10.70	14.00
Lajeado Mix No.4	140	140	1.00	13.00	16.50
Lajeado Mix No.5	160	160	1.00	15.90	19.80

Table B.3 Compressive Strength vs. W/C Ratio of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^3)	Water content (kg/m^3)	Water/Cementitious (w/c) Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Lajeado Mix No.6	180	180	1.00	24.20	29.00
Lajeado Mix No.7	180	180	1.00	24.50	33.00
Three Gorges Mix.1	198	89	0.45	27.60	36.20
Three Gorges Mix.2	196	88	0.45	23.90	31.60
Three Gorges Mix.3	193	87	0.45	19.30	23.40
Three Gorges Mix.4	178	89	0.50	23.60	32.80
Three Gorges Mix.5	176	88	0.50	21.50	28.00
Three Gorges Mix.6	174	87	0.50	15.90	22.90
Three Gorges Mix.7	162	89	0.55	19.10	28.30
Three Gorges Mix.8	160	88	0.55	12.70	23.50
Three Gorges Mix.9	158	87	0.55	10.10	18.60
Three Gorges Mix.10	160	72	0.45	29.10	37.00
Three Gorges Mix.11	158	71	0.45	25.20	33.00
Three Gorges Mix.12	155	70	0.45	21.00	25.00
Three Gorges Mix.13	144	72	0.50	24.50	33.40
Three Gorges Mix.14	142	71	0.50	21.90	30.10
Three Gorges Mix.15	140	70	0.50	15.80	20.20
Three Gorges Mix.16	131	72	0.55	22.50	28.00
Three Gorges Mix.17	130	71	0.55	15.40	24.00
Three Gorges Mix.18	127	70	0.55	12.90	20.00
Linhekou Mix 1	185	87	0.47	18.00	26.70
Linhekou Mix 2	172	81	0.47	18.90	25.30
Longtan Trial Mix 1 with retarding superplasticizer	191	80	0.42	27.30	42.60
Longtan Trial Mix 2 with air entering agent	191	80	0.42	27.50	40.06

Table B.3 Compressive Strength vs. W/C Ratio of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^{3})	Water content (kg/m^{3})	Water/Cementitious (w/c) Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Longtan Trial Mix 3 with retarding superplasticizer	160	80	0.50	16.40	26.40
Longtan Trial Mix 4 with air entering agent	160	80	0.50	17.70	28.00
Villarpando	90	105	1.17	8.85	11.50
Concepción	90	93	1.03	5.50	7.60
Jahgin Stage 1 Mix 1	195	140	0.72	6.50	11.50
Jahgin Stage 2 RCC 1-1 with Khash Natural Pozzolan	225	130	0.58	13.00	19.00
Badovli	160	115	0.72	9.00	11.50
Sa Stria Mix.1	227	139	0.61	9.60	15.70
Sa Stria Mix.2	212	123	0.58	8.60	16.40
Sa Stria Mix.3	215	140	0.65	11.40	18.40
Sa Stria Mix.4	210	124	0.59	10.50	20.00
Sa Stria Mix.5	212	140	0.66	12.30	19.90
Sa Stria Mix.6	223	140	0.63	14.10	21.40
Sa Stria Mix.7	234	142	0.61	21.90	24.30
Sa Stria Mix.8	230	133	0.58	8.30	12.90
Sa Stria Mix.9	230	129	0.56	10.60	17.90
Sa Stria Mix.10	230	124	0.54	12.90	19.50
Sa Stria Mix.11	230	124	0.54	7.10	11.30
Sa Stria Mix.12	230	120	0.52	9.00	13.50
Sa Stria Mix.13	230	117	0.51	11.50	18.70

Table B.3 Compressive Strength vs. W/C Ratio of RCC Dams (continued)

Dam Name	Cementitious content (Cement+Pozzolan,kg/m^3)	Water content (kg/m^3)	Water/Cementitious (w/c) Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Nunome	120	95	0.79	7.50	14.00
Nunome Mix 1	140	117	0.84	12.50	17.50
Nunome Mix 2	140	113	0.81	7.70	15.20
Nunome Mix 3	140	111	0.79	7.30	14.20
Nunome Mix 4	140	107	0.76	7.30	14.00
El Zapotillo Mix 1	331	86	0.26	11.00	14.00
El Zapotillo Mix 2	350	87	0.25	12.00	16.00
El Zapotillo Mix 3	368	87	0.24	13.00	17.00
Pedrógão Mix 1	200	120	0.60	15.10	
Pedrógão Mix 4	180	130	0.72	8.00	
Pedrógão Mix 5	160	120	0.75	7.80	
El Esparragal	225	112.5	0.50	10.40	17.47
El Esparragal Mix.1	225	101	0.45	9.19	17.17
El Esparragal Mix.2	225	112.5	0.50	14.35	18.42
El Esparragal Mix.3	225	126	0.56	31.93	35.64
Middle Fork	66	95	1.44	8.80	
Galesville Mix 1	104	113	1.09	4.00	
Galesville Mix 2	133	113	0.85	5.70	
Stacy - spillway	187	154	0.82	18.10	
Stagecoach	148	138	0.93	2.40	
Naras Mix 1	125	105	0.84	10.80	
Naras Mix 2	150	105	0.70	15.10	
Naras Mix 3	175	105	0.60	18.00	
Naras Mix 4	200	105	0.53	21.90	
Silopi Mix 4	100	100	1.00	11.53	
Silopi Mix 1	120	100	0.83	15.55	
Silopi Mix 2	140	100	0.71	20.19	
Silopi Mix 3	160	100	0.63	26.46	

Table B.4 Compressive Strength vs. Pozzolan Percentage for RCC Dams

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Three Gorges Mix.1	198	0.40	27.60	36.20
Three Gorges Mix.2	196	0.50	23.90	31.60
Three Gorges Mix.3	193	0.60	19.30	23.40
Ghatghar pumped storage Mix No.9	220	0.30	14.70	24.60
Ghatghar pumped storage Mix No.10	220	0.40	11.20	21.20
Ghatghar pumped storage Mix No.11	220	0.50	8.50	18.40
Ghatghar pumped storage Mix No.12	220	0.60	7.10	15.80
Ghatghar pumped storage Mix No.13	220	0.70	5.10	8.80
Jahgin Stage 1 Mix 1	195	0.64	6.50	11.50
Jahgin Stage 1 Mix 2	195	0.51	9.00	12.50
Jahgin Stage 1 Mix 3	195	0.38	13.00	16.00
Jahgin Stage 1 Mix 4	195	0.26	14.00	20.00
Jahgin Stage 1 Mix 5	195	0.13	16.00	20.50
Jahgin Stage 1 Mix 6	190	0.00	18.50	24.00
Sa Stria Mix.8	230	0.64	8.30	12.90
Sa Stria Mix.9	230	0.60	10.60	17.90
Sa Stria Mix.10	230	0.55	12.90	19.50
Nunome Mix 1	140	0.00	12.50	17.50
Nunome Mix 2	140	0.30	7.70	15.20
Nunome Mix 3	140	0.35	7.30	14.20
Nunome Mix 4	140	0.40	7.30	14.00

Table B.4 Compressive Strength vs. Pozzolan Percentage for RCC Dams (continued)

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Yeywa Stage II Mix 1	220	0.75	11.00	
Yeywa Stage II Mix 2	220	0.73	11.00	16.00
Yeywa Stage II Mix 3	220	0.70	13.00	17.00
Yeywa Stage II Mix 4	220	0.68	15.00	20.00
Yeywa Stage II Mix 5	220	0.66	16.00	21.00
Son La Stage I Mix 0	225	0.80	7.00	14.50
Son La Stage I Mix 1	230	0.74	8.50	19.70
Son La Stage I Mix 2	230	0.63	13.50	20.00
Son La Stage I Mix 3	230	0.52	16.50	25.00
Son La Stage I Mix 4	230	0.41	21.00	32.00
Son La Stage I Mix 5	230	0.30	27.00	33.00
Beni Haroun	225	0.63	16.00	24.00
Galesville Mix 1	104	0.49	4.00	7.00
Galesville Mix 2	133	0.51	5.70	9.40
Upper Stillwater Mix 1	301	0.69	17.70	24.80
Upper Stillwater Mix 2	299	0.69	23.60	29.00
Upper Stillwater Mix 3	233	0.69	12.60	17.90
Upper Stillwater Mix 4	252	0.69	15.40	21.40
Upper Stillwater Mix 5	252	0.54	14.70	24.20
Upper Stillwater Mix 6	232	0.69	8.40	14.80

Table B.4 Compressive Strength vs. Pozzolan Percentage for RCC Dams (continued)

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Willow Creek Mix 2	151	0.31	14.20	27.30
Willow Creek Mix 3	267	0.30	23.50	30.80
Willow Creek Mix 4	66	0.29	8.10	11.90
Saluda dam remediation primary	163	0.55	4.31	7.76
Saluda dam remediation Mix 2	178	0.5	7.24	12.41
Pedrógão Mix 1	200	0.65	15.10	
Pedrógão Mix 4	180	0.72	8.00	
Pedrógão Mix 5	160	0.75	7.80	
Dona Francisca Mix.1	85	0.35	4.70	7.90
Dona Francisca Mix.3	90	0.36	4.80	8.60
Longtan Trial Mix 1	191	0.53	27.30	42.60
Longtan Trial Mix 3	160	0.65	16.40	26.40
Longshou Mix 1	205	0.53	25.80	34.40
Longshou Mix 2	171	0.66	20.80	27.50
Camp Dyer	163	0.5	10.10	
Stacy Spillway	187	0.33	18.10	21.40
New Big Cherry	152	0.5		10.34
Elkwater Fork Mix 1	148	0.6		10.34
Elkwater Fork Mix 2	184	0.6		17.24
Tannur Mix 2	170	0.29	16.70	19.80
Sama El-Serhan	181	0.47		9.40
Marathia	60	0.21	4.14	4.99
Urayama	130	0.3		31.00
Hiyoshi	120	0.3		27.00
Tomisato No.1	120	0.3		23.00
El Esparragal	225	0.70	10.40	17.47

Table B.4 Compressive Strength vs. Pozzolan Percentage for RCC Dams (continued)

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
El Esparragal Mix.1	225	0.75	9.19	17.17
El Esparragal Mix.2	225	0.65	14.35	18.42
Elk Creek	84	0.2	3.00	9.00
Santa Cruz	151	0.5	8.90	15.00
Stagecoach	148	0.52	2.40	
Cana Brava	100	0.55	7.20	9.40
Pine Brook	154	0.38		10.34
Genesee Dam No.2	169	0.37		10.34
Hickory Log Creek Mix 2	178	0.55		13.79
Cenza	200	0.65	19.40	29.00
Porce II	220	0.4	16.00	19.80
Olivenhain	195	0.62	8.27	15.86
Olivenhain Mix.1	195	0.62	10.00	14.82
Olivenhain Mix.2	195	0.62	7.58	12.41
Olivenhain Mix.3	195	0.62	6.76	12.06
El Zapotillo Mix 1	331	0.67	11.00	14.00
El Zapotillo Mix 2	350	0.63	12.00	16.00
El Zapotillo Mix 3	368	0.59	13.00	17.00
Shapai Mix 1	192	0.40	14.00	18.40
Shapai Mix 2	192	0.50	13.30	18.00
Linhekou Mix 1	185	0.65	18.00	26.70
Linhekou Mix 2	172	0.65	18.90	25.30
Zhaolaihe	210	0.6	13.10	29.20
Zhaolaihe	229	0.45	14.50	24.90
Wenquanbao	195	0.49	24.50	29.90
Wenquanbao	173	0.45	17.70	21.40
Puding	188	0.55	22.20	32.10
Bailianya	180	0.6	19.70	28.70

Table B.5 Compressive Strength Efficiency vs. Pozzolan Percentage for RCC Dams

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Three Gorges Mix.1	198	0.40	0.14	0.18	27.60	36.20
Three Gorges Mix.2	196	0.50	0.12	0.16	23.90	31.60
Three Gorges Mix.3	193	0.60	0.10	0.12	19.30	23.40
Ghatghar pumped storage Mix No.9	220	0.30	0.07	0.11	14.70	24.60
Ghatghar pumped storage Mix No.10	220	0.40	0.05	0.10	11.20	21.20
Ghatghar pumped storage Mix No.11	220	0.50	0.04	0.08	8.50	18.40
Ghatghar pumped storage Mix No.12	220	0.60	0.03	0.07	7.10	15.80
Ghatghar pumped storage Mix No.13	220	0.70	0.02	0.04	5.10	8.80
Jahgin Stage 1 Mix 1	195	0.64	0.03	0.06	6.50	11.50
Jahgin Stage 1 Mix 2	195	0.51	0.05	0.06	9.00	12.50
Jahgin Stage 1 Mix 3	195	0.38	0.07	0.08	13.00	16.00
Jahgin Stage 1 Mix 4	195	0.26	0.07	0.10	14.00	20.00
Jahgin Stage 1 Mix 5	195	0.13	0.08	0.11	16.00	20.50
Sa Stria Mix.8	230	0.64	0.04	0.06	8.30	12.90
Sa Stria Mix.9	230	0.60	0.05	0.08	10.60	17.90
Sa Stria Mix.10	230	0.55	0.06	0.08	12.90	19.50
Nunome Mix 2	140	0.30	0.06	0.11	7.70	15.20
Nunome Mix 3	140	0.35	0.05	0.10	7.30	14.20
Nunome Mix 4	140	0.40	0.05	0.10	7.30	14.00
Yeywa Stage II Mix 1	220	0.75	0.05		11.00	
Yeywa Stage II Mix 2	220	0.73	0.05	0.07	11.00	16.00
Yeywa Stage II Mix 3	220	0.70	0.06	0.08	13.00	17.00
Yeywa Stage II Mix 4	220	0.68	0.07	0.09	15.00	20.00
Yeywa Stage II Mix 5	220	0.66	0.07	0.10	16.00	21.00

Table B.5 Compressive Strength Efficiency vs. Pozzolan Percentage for RCC Dams (continued)

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
El Esparragal Mix.1	225	0.75	0.04	0.08	9.19	17.17
El Esparragal Mix.2	225	0.65	0.06	0.08	14.35	18.42
Son La Stage I Mix 0	225	0.80	0.03	0.06	7.00	14.50
Son La Stage I Mix 1	230	0.74	0.04	0.09	8.50	19.70
Son La Stage I Mix 2	230	0.63	0.06	0.09	13.50	20.00
Son La Stage I Mix 3	230	0.52	0.07	0.11	16.50	25.00
Son La Stage I Mix 4	230	0.41	0.09	0.14	21.00	32.00
Son La Stage I Mix 5	230	0.30	0.12	0.14	27.00	33.00
Galesville Mix 1	104	0.49	0.04	0.07	4.00	7.00
Galesville Mix 2	133	0.51	0.04	0.07	5.70	9.40
Upper Stillwater Mix 1	301	0.69	0.06	0.08	17.70	24.80
Upper Stillwater Mix 2	299	0.69	0.08	0.10	23.60	29.00
Upper Stillwater Mix 3	252	0.69	0.06	0.10	14.70	24.20
Upper Stillwater Mix 4	252	0.69	0.06	0.08	15.40	21.40
Upper Stillwater Mix 5	233	0.54	0.05	0.08	12.60	17.90
Upper Stillwater Mix 6	232	0.69	0.04	0.06	8.40	14.80
Willow Creek Mix 2	151	0.31	0.09	0.18	14.20	27.30
Willow Creek Mix 3	267	0.30	0.09	0.12	23.50	30.80
Willow Creek Mix 4	66	0.29	0.12	0.18	8.10	11.90
Ghatghar pumped storage Mix No.1	180	0.40	0.06	0.08	11.00	14.10
Ghatghar pumped storage Mix No.2	180	0.50	0.05	0.07	9.60	13.00
Ghatghar pumped storage Mix No.3	180	0.60	0.05	0.07	9.00	12.70

Table B.5 Compressive Strength Efficiency vs. Pozzolan Percentage for RCC Dams (continued)

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Ghatghar pumped storage Mix No.4	180	0.70	0.04	0.06	6.80	10.50
Ghatghar pumped storage Mix No.5	200	0.40	0.07	0.11	14.40	21.20
Ghatghar pumped storage Mix No.6	200	0.50	0.06	0.10	11.90	19.50
Ghatghar pumped storage Mix No.7	200	0.60	0.05	0.08	9.30	15.00
Ghatghar pumped storage Mix No.8	200	0.70	0.04	0.06	7.30	12.40
Ghatghar pumped storage Mix No.14	240	0.40	0.06	0.09	15.00	21.50
Ghatghar pumped storage Mix No.15	240	0.50	0.07	0.09	17.00	22.60
Ghatghar pumped storage Mix No.16	240	0.60	0.05	0.08	11.60	18.70
Ghatghar pumped storage Mix No.17	240	0.70	0.03	0.05	8.20	11.40
Saluda dam remediation primary	163	0.55	0.03	0.05	4.31	7.76
Saluda dam remediation Mix 2	178	0.50	0.04	0.07	7.24	12.41
Marathia	70	0.21	0.06	0.06	4.14	4.14
Ano Mera	70	0.21	0.07	0.07	4.99	4.99
Dona Francisca Mix.1	85	0.35	0.06	0.09	4.70	7.90
Dona Francisca Mix.2	85	0.35	0.05	0.10	4.40	8.80
Dona Francisca Mix.3	90	0.36	0.05	0.10	4.80	8.60
Dona Francisca Mix.4	90	0.36	0.05	0.10	4.80	9.00

Table B.5 Compressive Strength Efficiency vs. Pozzolan Percentage for RCC Dams (continued)

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
Dona Francisca Mix.5	100	0.35	0.06	0.11	5.50	11.40
Dona Francisca Mix.6	90	0.36	0.05	0.08	4.40	7.30
Dona Francisca Mix.7	94	0.34	0.05	0.08	4.40	7.50
Dona Francisca Mix.8	94	0.34	0.05	0.09	4.50	8.00
Dona Francisca Mix.9	94	0.34	0.05	0.09	5.10	8.50
Dona Francisca Mix.10	100	0.35	0.05	0.09	5.00	8.80
Beni Haroun	225	0.63	0.07	0.11	16.00	24.00
Saluda dam remediation primary	163	0.55	0.03	0.05	4.31	7.76
Saluda dam remediation Mix 2	178	0.5	0.04	0.07	7.24	12.41
Pedrógão Mix 1	200	0.65	0.08		15.10	
Pedrógão Mix 4	180	0.72	0.04		8.00	
Pedrógão Mix 5	160	0.75	0.05		7.80	
Dona Francisca Mix.1	85	0.35	0.06	0.09	4.70	7.90
Dona Francisca Mix.3	90	0.36	0.05	0.10	4.80	8.60
Longtan Trial Mix 1	191	0.53	0.14	0.22	27.30	42.60
Longtan Trial Mix 3	160	0.65	0.10	0.17	16.40	26.40
Longshou Mix 1	205	0.53	0.13	0.17	25.80	34.40
Longshou Mix 2	171	0.66	0.12	0.16	20.80	27.50
Camp Dyer	163	0.5	0.06	0.00	10.10	
Stacy Spillway	187	0.33	0.10	0.11	18.10	21.40
New Big Cherry	152	0.5		0.07		10.34
Elkwater Fork Mix 1	148	0.6		0.07		10.34
Elkwater Fork Mix 2	184	0.6		0.09		17.24
Tannur Mix 2	170	0.29	0.10	0.12	16.70	19.80
Sama El-Serhan	181	0.47	0.00	0.05		9.40
Marathia	60	0.21	0.07	0.08	4.14	4.99
Urayama	130	0.3	0.00	0.24		31.00
Hiyoshi	120	0.3	0.00	0.23		27.00
Tomisato No.1	120	0.3	0.00	0.19		23.00

Table B.5 Compressive Strength Efficiency vs. Pozzolan Percentage for RCC Dams (continued)

Dam Name	Total Cementitious Content (kg/m^3)	Pozzolan/Cementitious Content Ratio	Str. Efficiency (MPa/kg) 28 days	Str. Efficiency (MPa/kg) 90 days	Compressive strength (MPa) for 28 days	Compressive strength (MPa) for 90 days
El Esparragal	225	0.70	0.05	0.08	10.40	17.47
El Esparragal Mix.1	225	0.75	0.04	0.08	9.19	17.17
El Esparragal Mix.2	225	0.65	0.06	0.08	14.35	18.42
Elk Creek	84	0.2	0.04	0.11	3.00	9.00
Santa Cruz	151	0.5	0.06	0.10	8.90	15.00
Stagecoach	148	0.52	0.02	0.00	2.40	
Cana Brava	100	0.55	0.07	0.09	7.20	9.40
Pine Brook	154	0.38		0.07		10.34
Genesee Dam No.2	169	0.37		0.06		10.34
Hickory Log Creek Mix 2	178	0.55		0.08		13.79
Cenza	200	0.65	0.10	0.15	19.40	29.00
Porce II	220	0.4	0.07	0.09	16.00	19.80
Olivenhain	195	0.62	0.04	0.08	8.27	15.86
Olivenhain Mix.1	195	0.62	0.05	0.08	10.00	14.82
Olivenhain Mix.2	195	0.62	0.04	0.06	7.58	12.41
Olivenhain Mix.3	195	0.62	0.03	0.06	6.76	12.06
El Zapotillo Mix 1	331	0.67	0.03	0.04	11.00	14.00
El Zapotillo Mix 2	350	0.63	0.03	0.05	12.00	16.00
El Zapotillo Mix 3	368	0.59	0.04	0.05	13.00	17.00
Shapai Mix 1	192	0.40	0.07	0.10	14.00	18.40
Shapai Mix 2	192	0.50	0.07	0.09	13.30	18.00
Linhekou Mix 1	185	0.65	0.10	0.14	18.00	26.70
Linhekou Mix 2	172	0.65	0.11	0.15	18.90	25.30
Zhaolaihe	210	0.6	0.06	0.14	13.10	29.20
Zhaolaihe	229	0.45	0.06	0.11	14.50	24.90
Wenquanbao	195	0.49	0.13	0.15	24.50	29.90
Wenquanbao	173	0.45	0.10	0.12	17.70	21.40
Puding	188	0.55	0.12	0.17	22.20	32.10
Bailianya	180	0.6	0.11	0.16	19.70	28.70

Table B.6 Direct Tensile Strength of RCC Dams (MPa)

Dam/Project	at 7 day	at 28 day	at 90 day	at 180 day	at 365 day
Beni Haroun			1.84		
Porce II			2.30		
Shapai Mix 1			2.05		
Platanovryssi			1.77		
Olivenhain					1.54
Upper Stillwater Mix 3					1.40
Mianhuatan Mix 1					1.40
Cana Brava Dam Mix 8.2.9	0.46	0.91	1.28	1.44	
Cana Brava Dam Mix 8.2.10	0.54	0.89	1.29	1.01	
Cana Brava Dam Mix 8.2.14	0.76	1.52	1.58		
Cana Brava Dam Mix 8.2.15	0.70	1.34			
Lajeado Mix No.1			0.45		
Miel I Mix 1	1.10		2.00		2.40
Miel I Mix 2	0.80		1.40		2.00
Miel I Mix 3	0.60		1.00		1.60
Miel I Mix 4	0.40		0.80		1.40
Porce III Lab.Mix No.1				0.73	
Porce III Lab.Mix No.2				1.25	
Capanda Mix.4					1.66
Capanda Mix.3					1.89
Three Gorges Mix.1		2.41	2.80		
Three Gorges Mix.2		1.81	2.47		
Three Gorges Mix.3		1.62	2.19		
Three Gorges Mix.4		2.09	2.61		
Three Gorges Mix.5		1.91	2.26		
Three Gorges Mix.6		1.54	2.15		
Three Gorges Mix.7		1.34	2.33		
Three Gorges Mix.8		1.16	1.98		

Table B.6 Direct Tensile Strength of RCC Dams (MPa) (continued)

Dam/Project	at 7 day	at 28 day	at 90 day	at 180 day	at 365 day
Three Gorges Mix.9		0.73	1.69		
Three Gorges Mix.10		2.42	2.75		
Three Gorges Mix.11		1.95	2.49		
Three Gorges Mix.12		1.65	2.21		
Three Gorges Mix.13		2.19	2.39		
Three Gorges Mix.14		1.92	2.30		
Three Gorges Mix.15		1.71	1.95		
Three Gorges Mix.16		1.52	2.25		
Three Gorges Mix.17		1.36	1.97		
Three Gorges Mix.18		0.95	1.64		
Mujib	0.31	0.46	0.69	0.89	1.10
El Esparragal			1.19		
El Esparragal Mix.1			1.61		
El Esparragal Mix.2			1.49		
El Esparragal Mix.3			2.67		
Olivenhain	0.46	0.61	0.95	1.23	1.58
Naras Mix 3	1.20	2.00	2.30	2.60	
Naras Mix 4	1.70	2.00	2.50	2.80	

Table B.7 Indirect Tensile Strength of RCC Dams (MPa)

Dam/Project	at 7 day	at 14 day	at 28 day	at 56 day	at 90 day	at 180 day	at 365 day
Porce III Lab.Mix No.1						1.00	
Porce III Lab.Mix No.2						1.54	
Ralco Lab. Mix.No.1	1.08		1.58	1.82	2.09		
Ralco Lab. Mix.No.2	1.33		1.78	2.16	2.21	2.87	
Ralco Lab. Mix.No.3	1.55		2.00	2.23	2.44		
Ralco Lab. Mix.No.4	1.86		2.34	2.72	2.78	3.46	
Sama El-Serhan				0.89-0.81(core)			
Saluda dam remediation primary	0.45	0.62	0.76	1.17	1.45	1.86	2.24
Saluda dam remediation Mix 2	0.76	0.86	1.10	1.45	1.72	2.14	
Cenza	1.24		2.25				
Three Gorges Mix.1	1.10		2.02		2.61		
Three Gorges Mix.2	0.79		1.34		2.25		
Three Gorges Mix.3	0.53		1.17		2.02		
Three Gorges Mix.4	0.79		2.04		2.18		
Three Gorges Mix.5	0.72		1.80		2.10		
Three Gorges Mix.6	0.48		1.40		2.00		
Three Gorges Mix.7	0.72		1.44		1.81		
Three Gorges Mix.8	0.61		0.90		1.57		
Three Gorges Mix.9	0.42		0.81		1.43		
Three Gorges Mix.10	1.12		2.10		2.59		
Three Gorges Mix.11	1.00		1.41		2.24		
Three Gorges Mix.12	0.71		1.19		2.13		
Three Gorges Mix.13	0.83		2.09		2.40		
Three Gorges Mix.14	0.73		1.90		2.15		
Three Gorges Mix.15	0.50		1.51		2.05		
Three Gorges Mix.16	0.70		1.43		1.90		
Three Gorges Mix.17	0.63		1.06		1.55		
Three Gorges Mix.18	0.45		0.90		1.49		
Miel I Mix.1	1.23		1.60		1.90	2.20	2.30
Miel I Mix.2	1.00		1.35		1.75	1.92	2.10
Miel I Mix.3	0.70		1.00		1.30	1.52	1.73
Miel I Mix.4	0.62		0.80		1.10	1.28	1.45
Mujib	0.61	0.73	0.84		1.19	1.49	1.74
El Esparragal					1.76		
El Esparragal Mix.1					1.64		
El Esparragal Mix.2					1.66		
El Esparragal Mix.3					3.23		

Table B.7 Indirect Tensile Strength of RCC Dams (MPa) (continued)

Dam/Project	at 7 day	at 14 day	at 28 day	at 56 day	at 90 day	at 180 day	at 365 day
Sa Stria Mix.2					2.00		
Sa Stria Mix.4					2.90		
Sa Stria Mix.8					1.50		
Sa Stria Mix.9					1.90		
Sa Stria Mix.10					2.30		
Sa Stria Mix.11					1.30		
Sa Stria Mix.12					1.70		
Sa Stria Mix.13					2.20		
Nordlingaalda Mix.1	0.70		1.00		1.80		
Nordlingaalda Mix.2	1.25		1.30		2.60		
Nordlingaalda Mix.3	1.45		1.80		2.40		
Nordlingaalda Mix.4	2.30		3.60		5.50		
Longtan Trial Mix 1 Lay Interval Time = 0 hr			2.84		3.58		
Longtan Trial Mix 1 Lay Interval Time = 6 hr			2.80		3.67		
Longtan Trial Mix 1 Lay Interval Time = 12 hr			2.55		3.13		
Longtan Trial Mix 1 Lay Interval Time = 24 hr			1.62		1.72		
Longtan Trial Mix 1 Lay Interval Time = 48 hr			1.99		2.97		
Longtan Trial Mix 2 Lay Interval Time = 0 hr			2.70		3.41		
Longtan Trial Mix 2 Lay Interval Time = 6 hr			2.43		3.33		
Longtan Trial Mix 2 Lay Interval Time = 12 hr			2.46		2.76		
Longtan Trial Mix 2 Lay Interval Time = 24 hr			1.05		1.81		
Longtan Trial Mix 2 Lay Interval Time = 48 hr			1.65		2.87		
Longtan Trial Mix 3 Lay Interval Time = 0 hr			1.66		2.56		
Longtan Trial Mix 3 Lay Interval Time = 6 hr			1.15		2.40		
Longtan Trial Mix 3 Lay Interval Time = 12 hr			1.34		1.54		

Table B.7 Indirect Tensile Strength of RCC Dams (MPa) (continued)

Dam/Project	at 7 day	at 14 day	at 28 day	at 56 day	at 90 day	at 180 day	at 365 day
Longtan Trial Mix 3 Lay Interval Time = 24 hr			0.66		0.93		
Longtan Trial Mix 3 Lay Interval Time = 48 hr			0.78		1.68		
Longtan Trial Mix 4 Lay Interval Time = 0 hr			1.56		2.72		
Longtan Trial Mix 4 Lay Interval Time = 6 hr			1.28		2.26		
Longtan Trial Mix 4 Lay Interval Time = 12 hr			1.41		2.04		
Longtan Trial Mix 4 Lay Interval Time = 24 hr			0.66		0.95		
Longtan Trial Mix 4 Lay Interval Time = 48 hr			0.80		1.78		
El Zapotillo Mix 1	0.80	1.20	1.40	1.70	2.00	2.35	
El Zapotillo Mix 2	0.90	1.30	1.50	1.90	2.20	2.50	
El Zapotillo Mix 3	1.20	1.45	1.70	2.20	2.35	2.70	
Yantan	0.93		2.34		2.71		
Shapai Mix 1			1.11		1.61		
Shapai Mix 2			1.09		1.53		
Shapai Mix 3			1.15		1.64		
Linhekou Mix 1					2.45		
Zhaolaihe Mix 1			1.63		2.71		
Zhaolaihe Mix 2			1.28		2.55		
Longshou Mix 1			2.10		3.01		
Wenquanbao Mix 1			1.92		2.71		
Wenquanbao Mix 2			2.41		2.76		
Wenquanbao Mix 3			2.22		2.91		
Puding			2.20		2.85		
Bailianya					1.97		
Cindere						0.60	
Naras Mix 1	0.90		1.50		1.90	2.10	
Naras Mix 2	1.00		1.90		2.40	2.70	
Naras Mix 3	1.40		2.60		3.10	3.50	
Naras Mix 4	1.80		2.80		3.60	4.00	
Silopi Mix 4	0.83		1.68		1.30	1.56	
Silopi Mix 1	1.58		2.12		2.36	2.83	
Silopi Mix 2	1.99		2.49		2.52	3.02	
Silopi Mix 3	2.22		2.66		3.44	4.13	

Table B.8 Indirect Tensile Strength vs. Cementitious Content

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Indirect tensile strength (MPa)
Ralco Lab. Mix.No.1	135	2.09
Ralco Lab. Mix.No.2	145	2.21
Ralco Lab. Mix.No.3	165	2.44
Ralco Lab. Mix.No.4	175	2.78
Saluda Dam primary	163	1.45
Saluda Dam Mix no 2	178	1.72
Three Gorges Mix.1	198	2.61
Three Gorges Mix.2	196	2.25
Three Gorges Mix.3	193	2.02
Three Gorges Mix.4	178	2.18
Three Gorges Mix.5	176	2.10
Three Gorges Mix.6	174	2.00
Three Gorges Mix.7	162	1.81
Three Gorges Mix.8	160	1.57
Three Gorges Mix.9	158	1.43
Three Gorges Mix.10	160	2.59
Three Gorges Mix.11	158	2.24
Three Gorges Mix.12	155	2.13
Three Gorges Mix.13	144	2.40
Three Gorges Mix.14	142	2.15
Three Gorges Mix.15	140	2.05
Three Gorges Mix.16	131	1.90
Three Gorges Mix.17	130	1.55
Three Gorges Mix.18	127	1.49
Miel I Mix.1	150	1.90
Miel I Mix.2	125	1.75
Miel I Mix.3	100	1.30
Miel I Mix.4	85	1.10
Mujib	85	1.19
El Esparragal	225	1.76
Nordlingaalda Mix.1	80	1.80

Table B.8 Indirect Tensile Strength vs. Cementitious Content (continued)

Dam Name	Cementitious content (Cement+Pozzolan, kg/m^{3})	Indirect tensile strength (MPa)
Nordlingaalda Mix.2	105	2.60
Nordlingaalda Mix.3	133	2.40
El Zapotillo Mix 1	331	2.00
El Zapotillo Mix 2	350	2.20
El Zapotillo Mix 3	368	2.35
Yantan	159	2.71
Shapai Mix 1	192	1.61
Shapai Mix 2	182	1.53
Linhekou	185	2.45
Zhaolaihe Mix 1	210	2.71
Zhaolaihe Mix 2	229	2.55
Wenquangpu Mix 1	152	2.71
Wenquangpu Mix 2	168	2.76
Naras Mix 1	125	1.90
Naras Mix 2	150	2.40
Naras Mix 3	175	3.10
Naras Mix 4	200	3.60
Silopi Mix 4	100	1.30
Silopi Mix 1	120	2.36
Silopi Mix 2	140	2.52
Silopi Mix 3	160	3.44
Sa Stria Mix.2	212	2.00
Sa Stria Mix.4	210	2.90
Sa Stria Mix.8	230	1.50
Longtan Trial Mix 1 Lay Interval Time = 0 hr	191	3.58
Longtan Trial Mix 2 Lay Interval Time = 0 hr	191	3.41
Longtan Trial Mix 3 Lay Interval Time = 0 hr	160	2.56
Longtan Trial Mix 4 Lay Interval Time = 0 hr	160	2.72
Puding	188	2.85
Bailianya	180	1.97

Table B.9 Indirect Tensile Strength to Compressive Strength Ratio for RCC Dams

Dam Name	Indirect tensile strength (MPa)	Compressive strength (MPa)	Indirect Tensile / Compressive Ratio
Saluda Dam primary	1.45	7.76	0.187
Saluda Dam Mix no 2	1.72	12.41	0.139
Three Gorges Mix.1	2.61	36.20	0.072
Three Gorges Mix.2	2.25	31.60	0.071
Three Gorges Mix.3	2.02	23.40	0.086
Three Gorges Mix.4	2.18	32.80	0.066
Three Gorges Mix.5	2.10	28.00	0.075
Three Gorges Mix.6	2.00	22.90	0.087
Three Gorges Mix.7	1.81	28.30	0.064
Three Gorges Mix.8	1.57	23.50	0.067
Three Gorges Mix.9	1.43	18.60	0.077
Three Gorges Mix.10	2.59	37.00	0.070
Three Gorges Mix.11	2.24	33.00	0.068
Three Gorges Mix.12	2.13	25.00	0.085
Three Gorges Mix.13	2.40	33.40	0.072
Three Gorges Mix.14	2.15	30.10	0.071
Three Gorges Mix.15	2.05	20.20	0.101
Three Gorges Mix.16	1.90	28.00	0.068
Three Gorges Mix.17	1.55	24.00	0.065
Three Gorges Mix.18	1.49	20.00	0.075
Miel I Mix.1	1.90	17.70	0.107
Miel I Mix.2	1.75	15.30	0.114
Miel I Mix.3	1.30	12.00	0.108
Miel I Mix.4	1.10	10.30	0.107

Table B.9 Indirect Tensile Strength to Compressive Strength Ratio for RCC Dams (continued)

Dam Name	Indirect tensile strength (MPa)	Compressive strength (MPa)	Indirect Tensile / Compressive Ratio
Mujib	1.19	8.44	0.141
El Esparragal	1.76	17.47	0.101
Nordlingaalda Mix.1	1.80	15.00	0.120
Nordlingaalda Mix.2	2.60	22.00	0.118
Nordlingaalda Mix.3	2.40	31.00	0.077
El Zapotillo Mix 1	2.00	14.00	0.143
El Zapotillo Mix 2	2.20	16.00	0.138
El Zapotillo Mix 3	2.35	17.00	0.138
Yantan	2.71	27.10	0.100
Shapai Mix 1	1.61	18.40	0.088
Shapai Mix 2	1.53	18.00	0.085
Linhekou	2.45	26.70	0.092
Zhaolaihe Mix 1	2.71	29.20	0.093
Zhaolaihe Mix 2	2.55	24.90	0.102
Wenquangpu Mix 1	2.71	21.40	0.127
Wenquangpu Mix 2	2.76	29.90	0.092
Naras Mix 1	1.90	13.90	0.137
Naras Mix 2	2.40	17.90	0.134
Naras Mix 3	3.10	22.20	0.140
Naras Mix 4	3.60	28.60	0.126
Silopi Mix 4	1.30	13.04	0.100
Silopi Mix 1	2.36	17.19	0.137
Silopi Mix 2	2.52	24.46	0.103
Silopi Mix 3	3.44	31.54	0.109
AVERAGE	**2.12**	**22.43**	**0.101**

Table B.10 Thermal Expansion Coefficients of Some RCC Dams

Dam/Project	Modulus of Thermal Expansion (E-6 /deg C)
Concepcion	3.40
Milltown Hill	1.80
Santa Cruz	1.70
Elk Creek Mix 2	2.20
Upper Stillwater Mix 4	2.70
Upper Stillwater Mix 5	2.70
Upper Stillwater Mix 6	2.20
Willow Creek Mix 1	2.20
Willow Creek Mix 2	2.20
Willow Creek Mix 3	2.20
Willow Creek Mix 4	2.20
Zintel Canyon Mix 4	2.30
Zintel Canyon Mix 5	2.40
Tannur	6.50
Miel I	7.00
Mianhuatan Lab Mix No.1	5.60
Mianhuatan Lab Mix No.2	6.60
Mianhuatan Lab Mix No.3	7.30
Mianhuatan Lab Mix No.4	7.80
Mianhuatan Lab Mix No.5	7.90
Mianhuatan Lab Mix No.6	8.20
Salto Caxias	7.07
Hinata	10.00
Rialb	7.80
Cana Brava	11.70
Wolwedans	10.00
Zhaolaihe	7.00
Badovli	8.80
Wudu	8.42
Yujianhe	6.48
Dahuashui	6.50
Platanovryssi	11.50
Urugua-i RCC60	7.40
Urugua-i RCC90	8.33
Al-Mujib	8.10

Table B.11 Modulus of Elasticity of Some RCC Dams (GPa)

Dam/Project	at 7 day	at 28 day	at 90 day	at 180 day	at 365 day
Concepcion Mix 2		7.58	13.17		22.82
Santa Cruz Mix 2	9.38	12.41	15.58		22.34
Upper Stillwater Mix 5		7.10	9.10		11.79
Upper Stillwater Mix 6		5.65			10.96
Upper Stillwater Mix 7		6.34			12.14
Urugua-i		15.51	21.51		24.82
Willow Creek Mix 1	15.17	18.41	19.17		
Willow Creek Mix 2	16.55	20.06	22.41		
Willow Creek Mix 3	8.27	10.96	13.17		
Zintel Canyon Mix 1	4.69	10.62	14.82		17.72
Zintel Canyon Mix 2	10.62	16.48	17.03		22.62
Ghatghar pumped storage Mix No.1		12.50	11.50		0.00
Ghatghar pumped storage Mix No.2		18.20	19.20		22.90
Ghatghar pumped storage Mix No.3		15.60	15.90		24.40
Ghatghar pumped storage Mix No.4		13.30	10.70		
Ghatghar pumped storage Mix No.5		25.00	22.00		24.10
Ghatghar pumped storage Mix No.6		24.00	21.00		21.00
Ghatghar pumped storage Mix No.7		9.60	17.60		21.80
Ghatghar pumped storage Mix No.8		6.00	8.40		23.10
Ghatghar pumped storage Mix No.9		29.00	40.80		42.10
Ghatghar pumped storage Mix No.10		21.00	35.50		40.90
Ghatghar pumped storage Mix No.11		31.00	26.90		42.20
Ghatghar pumped storage Mix No.12		20.00	27.70		45.50
Ghatghar pumped storage Mix No.13			27.20		50.10

Table B.11 Modulus of Elasticity of Some RCC Dams (GPa) (continued)

Dam/Project	at 7 day	at 28 day	at 90 day	at 180 day	at 365 day
Ghatghar pumped storage Mix No.14		19.00	19.80		19.10
Ghatghar pumped storage Mix No.15		35.00	40.00		33.30
Ghatghar pumped storage Mix No.16		14.80	25.60		21.70
Ghatghar pumped storage Mix No.17		20.20	15.00		16.70
Lajeado Mix No.1			21.30		
Kinta Dam			18.20		
Tannur Dam			18.00		
Mianhuatan Lab Mix No.1		17.20	22.40	26.70	
Mianhuatan Lab Mix No.2		22.20	26.60	29.30	
Mianhuatan Lab Mix No.3		23.60	27.70	31.50	
Mianhuatan Lab Mix No.4	16.30	22.50	28.80		
Mianhuatan Lab Mix No.5	18.60	25.20			
Mianhuatan Lab Mix No.6	23.70	31.20			
Miel I Mix 1	14.50		33.00		42.00
Miel I Mix 2	14.00		32.00		36.00
Miel I Mix 3	7.00		25.00		29.00
Miel I Mix 4	6.00		21.00		26.00
Porce III Lab.Mix No.1				6.90	
Porce III Lab.Mix No.2				11.40	
Sama El-Serhan		5.45-4.90 (core)			
Capanda Mix.1	6.00		25.00		
Cenza	10.20	15.10	19.10		
Three Gorges Mix.1	21.50	26.00	40.00		
Three Gorges Mix.2	16.90	22.80	35.30		
Three Gorges Mix.3	14.90	19.20	32.10		
Three Gorges Mix.4	17.40	25.10	38.40		
Three Gorges Mix.5	16.90	24.00	35.20		

Table B.11 Modulus of Elasticity of Some RCC Dams (GPa) (continued)

Dam/Project	at 7 day	at 28 day	at 90 day	at 180 day	at 365 day
Three Gorges Mix.6	14.40	21.30	31.50		
Three Gorges Mix.7	15.10	25.90	36.40		
Three Gorges Mix.8	13.00	22.40	33.30		
Three Gorges Mix.9	12.20	18.00	24.90		
Three Gorges Mix.10	22.00	25.20	38.90		
Three Gorges Mix.11	16.50	23.10	36.00		
Three Gorges Mix.12	15.00	19.20	33.30		
Three Gorges Mix.13	18.50	27.40	35.60		
Three Gorges Mix.14	15.50	25.70	34.30		
Three Gorges Mix.15	15.00	23.70	28.20		
Three Gorges Mix.16	15.00	26.20	36.20		
Three Gorges Mix.17	13.50	23.10	33.20		
Three Gorges Mix.18	12.30	19.00	25.00		
Miel I Mix.1	12.00	19.00	24.50	26.30	28.00
Miel I Mix.2	11.00	18.00	23.00	25.50	27.00
Miel I Mix.3	9.00	14.00	19.00	22.00	25.50
Miel I Mix.4	7.50	12.00	16.50	20.60	24.00
Mujib @25% Ultimate Load	8.00	19.00	21.60	26.20	29.00
Mujib @50% Ultimate Load	4.60	11.60	12.80	17.00	20.80
Mujib @75% Ultimate Load	2.60	6.80	7.80	11.00	14.60
Mujib @100% Ultimate Load	0.80	1.60	1.80	2.40	4.40
Yantan	15.10	26.40	30.00		

Table B.11 Modulus of Elasticity of Some RCC Dams (GPa) (continued)

Dam/Project	at 7 day	at 28 day	at 90 day	at 180 day	at 365 day
Shapai Mix 1		15.40	19.10		
Shapai Mix 2		15.20	19.80		
Shapai Mix 3		15.20	20.50		
Linhekou Mix 1					
Linhekou Mix 2					
Zhaolaihe Mix 1			29.20		
Zhaolaihe Mix 2			32.30		
Longshou Mix 1		27.80	34.20		
Longshou Mix 2			29.60		
Wenquanbao Mix 1			39.90		
Wenquanbao Mix 2			33.90		
Wenquanbao Mix 3			38.20		
Puding		35.30	39.20		
Bailianya		24.10	31.00		
Naras Mix 1			27.00	30.80	
Naras Mix 2			29.50	33.50	
Naras Mix 3			32.00	38.50	
Naras Mix 4			34.00	38.20	
Silopi Mix 1			28.70		
Silopi Mix 2			31.20		
Silopi Mix 3			21.60		
Nordlingaalda @25% Ultimate Load	8.00	19.00	21.60	26.20	29.00
Nordlingaalda @50% Ultimate Load	4.60	11.60	12.80	17.00	20.80
Nordlingaalda @75% Ultimate Load	2.60	6.80	7.80	11.00	14.60
Nordlingaalda @100% Ultimate Load	0.80	1.60	1.80	2.40	4.40

Table B.12 Aggregate Gradation Curve of Some RCC Dams

Sieve Size (mm)	Willow Creek	Upper Stillwater	Christian Siegrist	Zintel Canyon	Stagecoach	Concepcion	Elk Creek
0.075	5	0	5	9	5	6	7
0.15	7	2	6	11	8	9	10
0.3	9	10	10	12	10	15	15
0.6	13	17	14	15	15	19	21
1.18	17	21	23	18	25	25	31
2.36	23	26	38	25	32	33	34
4.75	30	35	49	39	40	43	41
9.5	42	45	60	50	52	56	51
12.5							
19	54	66	91	70	69	72	58
25	62		99	77	82	80	64
37	80	95	100	91	95	90	76
50	90	100		98	100	94	86
67				100			96
75	100					99	100
100						100	