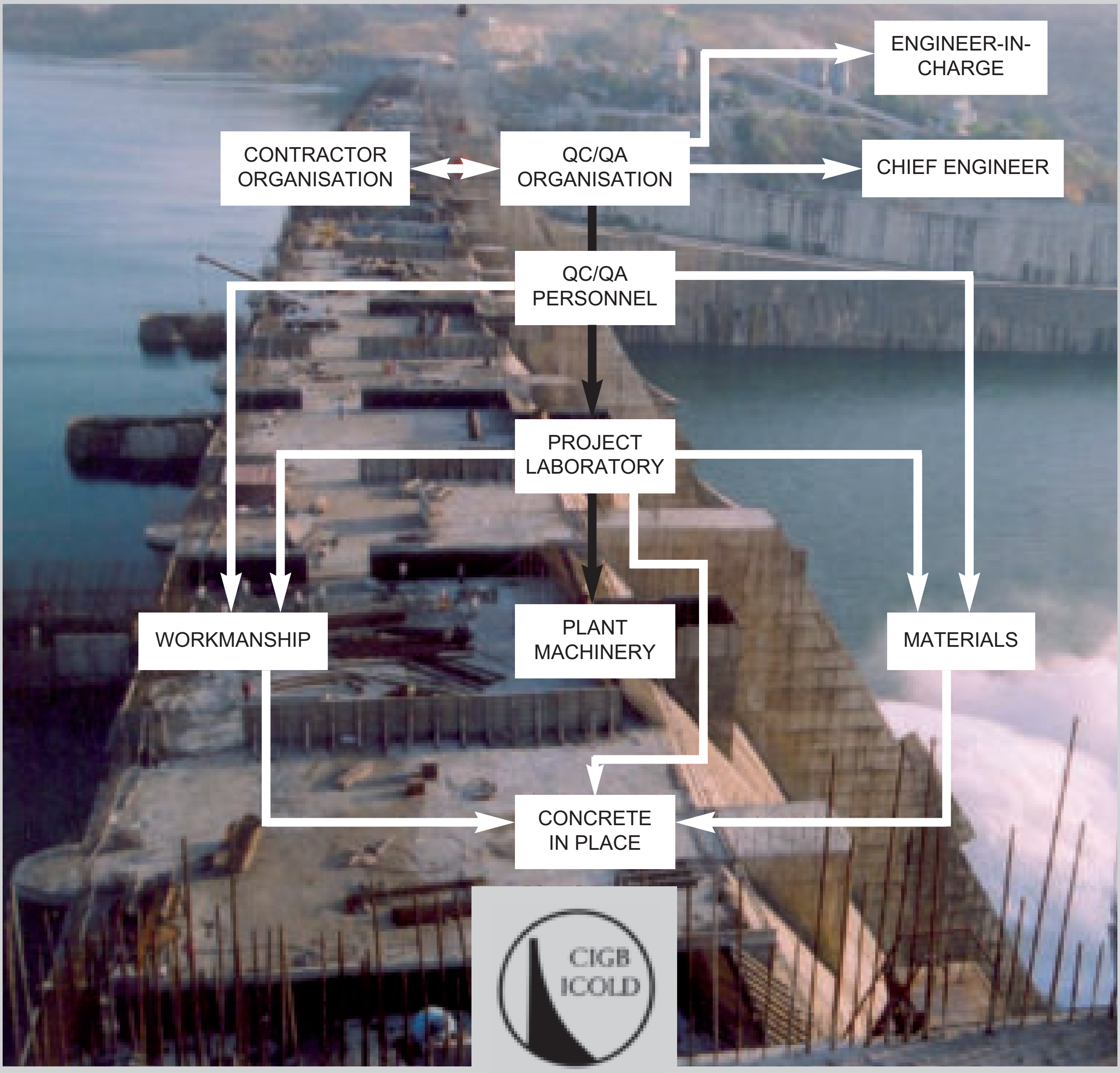
# THE SPECIFICATION AND QUALITY CONTROL OF CONCRETE FOR DAMS

# LES SPÉCIFICATIONS ET LE CONTRÔLE DE QUALITÉ DES BARRAGES EN BÉTON

## Bulletin 136



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Cover: Sardar Sarovar Dam (India)

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# THE SPECIFICATION AND QUALITY CONTROL OF CONCRETE FOR DAMS

# LES SPÉCIFICATIONS ET LE CONTRÔLE DE QUALITÉ DES BARRAGES EN BÉTON

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# AVANT-PROPOS

Ce Bulletin sur « les spécifications et le contrôle de qualité des barrages en béton » suit plus de deux décennies d'avancements dans la construction des barrages en béton. Le but de ce bulletin est de rendre disponible un résumé de la pratique en vigueur dans les spécifications et le contrôle de qualité des barrages en béton. Ce bulletin remplace le bulletin Nº 47 de la CIGB « Contrôle de la qualité du béton » édité en 1983.

En 1991, la Commission Internationale des Grands Barrages (ICOLD) a demandé au Comité Technique des Barrages en Béton, présidé par J.R. Graham (États-Unis), d'entreprendre la préparation d'une mise à jour du bulletin existant. Un sous-comité, présidé par J. Gaztenaga (Espagne), a préparé une première version du nouveau bulletin. En 1999 le Comité, présidé par R.G. Charlwood (Canada) était d'accord sur des révisions importantes des missions proposées par O.J. Berthelsen (Norvège) nommé à la tête du sous-comité et une nouvelle ébauche a été entreprise. Cette nouvelle ébauche était d'une portée plus large et traitait des spécifications du béton aussi bien que du contrôle de qualité.

Ce Bulletin aborde tous les aspects entre les spécifications du béton, les procédures de construction, les propriétés du béton durci et comment le contrôle de qualité est effectué. Le développement des barrages en béton depuis l'étape conceptuelle jusqu'au produit fini est décrit. Il présente une approche holistique, en corrélation avec le processus de conception et de construction et les rôles des concepteurs et des entrepreneurs dans la production du béton fonctionnel, durable et économique sont décrits. Les méthodes et approches d'exécution spécifiques sont identifiées aussi bien comme les options courantes dans l'attribution de la construction incluant la conception conventionnelle, l'offre et la construction, que dans des approches de conception-construction.

Des cas pratiques sont présentés pour un barrage-poids en béton vibré conventionnel (CVC), un barrage en béton compacté par rouleau (RCC), et un barrage-voûte en béton CVC. Les annexes donnent en tant que checklists possibles des tables des fréquences typiques d'essai, une liste de table des matières avec des spécifications complètes ainsi qu'une liste des conditions spécifiques exigées pour le contrôle de la fissuration.

Ce Bulletin présente la « situation actuelle » et laisse une ouverture pour toute nouvelle mise à jour.

ROBIN G. CHARLWOOD
Président,
Comité des Barrages en Béton

# FOREWORD

This Bulletin on the “ The Specification and Quality Control of Concrete for Dams ” follows more than two decades of advances in the construction of concrete dams. The purpose of this Bulletin is to make available a summary of current practice in the specification and quality control of concrete for dams. This Bulletin supersedes ICOLD Bulletin Nº47 ’Quality Control of Concrete’ published in 1983.

In 1991, the International Commission on Large Dams (ICOLD) directed that its technical Committee on Concrete for Dams, then under the Chairmanship of J.R. Graham (USA), undertake the preparation of an update of the existing Bulletin. A sub-Committee of the ICOLD Committee on Concrete for Dams, chaired by J. Gaztenaga (Spain), prepared a preliminary version of a new Bulletin. In 1999 the Committee, then under the Chairmanship of R.G. Charlwood (Canada) agreed to major revisions to the terms of reference proposed by O.J. Berthelsen (Norway) who was appointed to lead the sub-Committee and proceeded to prepare a new draft. The new draft was wider in scope and addressed the specification of concrete as well as practices for quality control.

This Bulletin addresses all aspects of the relationship between the specification of concrete, construction procedures, the properties of the hardened concrete and how quality control is used. The development of concrete for dams from the conceptual stage to finished product is described. It presents a holistic approach, recognizing the interrelatedness of the design and construction process and the roles of both Designers and Contractors in the production of functional, durable and economic concrete. Both method and performance approaches to specifications are recognised as well as current options in contracting for construction including conventional design, bid and construct as well as design-build approaches.

Case histories are presented for a gravity dam of conventional vibrated concrete (CVC), a roller compacted concrete (RCC) dam, and a CVC arch dam. Appendices give tables of typical test frequencies, a sample table of contents listing for a complete specification plus a listing of specific requirements for control of cracking are given as possible checklists.

This Bulletin presents the current “ State of the Art ” and does not intend to limit any further developments.

ROBIN G. CHARLWOOD
Chairman,
Committee on Concrete Dams

# REMERCIEMENTS

Ce Bulletin a été rédigé sous les auspices du Comité des Barrages en Béton de la CIGB et sous la présidence de R.G. Charlwood (Canada/USA).

L'auteur principal du Bulletin est O.J. Berthelsen (Norvège). Le projet de bulletin sous sa forme actuelle a été entrepris par O.J. Berthelsen utilisant une précédente ébauche de J.M. Gaztanaga (Espagne) en 2000. Des contributions et les révisions ont été fournies par B. Forbes (Australie), H. Kreuzer (Suisse), B.J. Parmar (Inde), Malcolm Dunstan (Royaume-Uni), M.R. Jabarooti (Iran) et J. Launay (France).

Les cas pratiques ont été apportés par B.J. Parmar (Inde) pour le barrage de Sardar Sarovar, Bruce Bennett et James Stiady (États-Unis) pour le barrage d'Olivenhain, et A. Camelo (Portugal) pour le barrage d'Alqueva. Le Comité remercie les propriétaires de ces barrages, Sardar Sarovar Narmada Nigam Ltd. pour le barrage de Sardar Sarovar, l'administration des eaux de San Diego pour le barrage d'Olivenhain, et EDIA Empresa de Desenvolvimento e Infraestruturas do Alqueva, SA pour le barrage d'Alqueva, et pour l'autorisation d'éditer ces études de cas.

# ACKNOWLEDGEMENTS

This Bulletin was drafted under the auspices of the ICOLD Committee for Concrete Dams and the Chairmanship of R.G. Charlwood (Canada/USA).

The lead author of the Bulletin was O.J. Berthelsen (Norway). The first draft of the Bulletin in its current form was assembled by O.J. Berthelsen utilising a previous draft by J.M. Gaztanaga (Spain) in 2000. Contributions and reviews were provided by B. Forbes (Australia), H. Kreuzer (Switzerland), B. J. Parmar (India), Malcolm Dunstan (United Kingdom), M. R. Jabarooti (Iran) and J. Launay (France).

The case histories were provided by B. J. Parmar (India) for Sardar Sarovar, Bruce Bennett and James Stiady (United States) for Olivenhain Dam, and A. Camelo (Portugal) for Alqueva Dam. The Committee thanks the owners of these dams, Sardar Sarovar Narmada Nigam Ltd. for Sardar Sarovar Dam, San Diego Water Authority for Olivenhain Dam, and EDIA Empresa de Desenvolvimento e Infraestruturas do Alqueva, S.A. for Alqueva Dam, for permission to publish these case histories.

# 1. INTRODUCTION

## 1.1. OBJECTIVES

This Bulletin is concerned with the relationship between the specification of concrete, construction procedures, the properties of the hardened concrete and how quality control is used. The development of concrete for dams from the conceptual stage to finished product is described. A holistic understanding of the interrelatedness of the design and construction process is important for both designers and contractors for functional, durable and economic concrete to be obtained.

Central to achieving concrete for dams with the required properties is acknowledgement that the properties of any concrete formulation are a compromise made in the design. Not all desired properties can be achieved in full measure. Undue focus on one property can lead to another undesired property. The obvious instance is high strength concrete, with its high cement content, will also yield a high temperature with increased risk of cracking when placed in thick sections.

Rates of construction can be very high. Acceptance or rejection of concrete based on strength tests after a long curing period is often not a realistic proposition. At the time of acceptance or refusal, the concrete may be buried under many metres of subsequent placements, making removal expensive and time-consuming. Typically, concrete for dams has to be approved based on its constituents, the properties of the fresh concrete and placement procedures with correlations between these factors and long-term strength gain, and not on strength requirements alone.

Concrete which is specific to dams is covered in this Bulletin. Such concrete is mass concrete for dam bodies and other massive hydraulic structures, and concrete for hydraulic surfaces including spillways. Structural concrete has a minor role in dams. Its manufacture and use is covered by various national and international standards and codes and is not included in this Bulletin. As this Bulletin covers concrete as a material, other aspects such as steel reinforcement and formwork are not included.

This Bulletin supersedes ICOLD Bulletin N° 47, Quality Control of Concrete.

## 1.2. THE CONTENTS OF THE BULLETIN

The specification and quality control system is described. This is followed by a chapter on the constituent materials of concrete and concrete manufacture and then by chapters on transport and placement, control of strength, thermal crack control and other aspects. Chapters on spillway chute concrete and case histories illustrating the implementation of specification and quality control for four projects complete the text.

Reference is made to specification and quality control of concrete in general, but only issues that are of particular importance or unique to concrete for dams are treated in detail.

## 1.3. QUALITY CONTROL AND QUALITY ASSURANCE

Quality control refers to those measures required to verify that the specification requirements are met. Quality assurance includes activities and systems needed to verify that the quality control measures have been performed and that the basis for the quality control is appropriate.

The International Standards Organisation (ISO) defines four levels of quality control:

| | |
|---|---|
| Level 1 | activity limited to the quality of the final product |
| Level 2 | Level 1 plus control of the production process |
| Level 3 | extends the control to the construction management |
| Level 4 | includes the whole management such as flow of information, authority, quality of personnel, training etc. of all parties involved |

This Bulletin deals with all four levels of quality control, but with emphasis on the link between design and specification and final constructed quality.

## 1.4. DEFINITIONS

A number of terms used in this Bulletin are defined here in the interests of clarity.

| | |
|---|---|
| Owner | is used here in the strict sense of the word. Depending on context, it may also mean developer |
| Owner's Representative | the body that acts on behalf of the Owner and may be the Designer or Project Manager |
| Project Manager | is the body that that manages the project on behalf of the Owner for either a conventional or turnkey/EPC type of contract |
| Designer | is the body that designs and specifies the work for a conventional type of contract. This body may also be responsible for supervision of the work, but this activity may be assigned to others (e.g. construction manager) |
| Contractor | is the body that builds the works including supply of permanent equipment. There may be more than one Contractor engaged on the projects |
| Regulator | is the body responsible for conformance with laws and regulations aimed at ensuring public safety and environmental acceptance |

| | |
|---|---|
| Quality | is the totality of concrete characteristics that bear on its ability to satisfy the required performance |
| Quality Control | refers to operational techniques and activities that are used to satisfy quality requirements |
| Quality Assurance | refers to all measures oriented to achieve quality and, in particular, to detect and avoid errors in all stages of the design and construction process |

## 1.5. RELATED BULLETINS

| | |
|---|---|
| Bulletin N° 107 | *Concrete dams - Control and treatment of cracks* |
| Bulletin N° 110 | *Cost impact of rules, criteria and specifications - Review and recommendations* |
| Bulletin N° 126 | *The State of the art of Roller Compacted Concrete* |

# 2. THE SPECIFICATION AND QUALITY CONTROL PROCESS

## 2.1. THE CONTENT OF SPECIFICATIONS

Specifications contain three elements that are required to achieve the desired product.

1. The technical specification contains a description of the end product, its constituents and manufacturing process. With the drawings of the works, this is the principal output of the analysis and design phase.
2. The quality control part of the specification describes what to measure and what to inspect, how these activities are to be executed, results evaluated and what action shall be taken. This includes reference to codes and standards that apply and submittals that are required for review and approval. This part of the specification is derived from experience of construction and knowledge of good practice.
3. The specification deals with the organisation of the quality control body, its powers, resources, communications and requirements for documentation. This is in essence the quality assurance system as it applies to the construction of the works.

In a method specification all these elements may be given in some detail, whereas in a performance specification the description of the manufacturing process and concrete constituents may be reduced, even substantially. These two types of specification are discussed in more detail in Section 0.

The commercial aspects of the specification (methods of measurement and payment) are not dealt with here, but are an important aspect when considering the ability to achieve successful quality control. Methods of measurement and payment that encourage the Contractor to provide effective quality control of his own work should be included.

For dam projects where structural and mass concrete will be placed within the same contract, it can be beneficial to prepare a separate specification which applies to the particularities of concrete in the dam as covered by this Bulletin.

The *materials and products* part of the specification contains the technical requirements of construction materials and products. The provisions in this part are usually taken from design studies and investigations and are based on the technical needs and economic factors specific to the project and site. Quality requirements must take account of the properties of available materials. Maximum and minimum limits and allowable deviations on properties or characteristics of the materials must be specified to provide the degree of control required by the design. Reference is often made to commonly accepted national or international standards that contain many of these limits or allowed deviations (but should be used only after careful evaluation of the appropriateness of their provisions by the designer). The objective of this part of the specification is to incorporate reasonable limits on those items that may be expected to influence variation in, and quality of the final product.

The content of the *execution* part of the specification will depend on whether a method or performance type of specification is used. In a performance specification this part may be minimal. A method specification will include provisions for required equipment and methods for performing the various construction operations associated with completing the work. It provides a step-by-step procedure for accomplishing the work and includes any construction constraints and allowed tolerances. Where the Contractor is responsible for quality control testing, a method specification will include the tests to be made, testing standards to be followed, testing frequencies and required visual inspections to confirm compliance with the specification. It also describes the action to be taken if test results or inspections show that materials or work do not comply with specification requirements.

## 2.2. PURPOSE OF QUALITY CONTROL

The purpose of concrete quality control is to maintain uniformity (minimising variation) of all constituents and operations entering into the final product such that the final product will have predictable properties and behaviour, and will satisfy the design requirements. Quality control of concrete is commonly measured by the variation in compressive strength results as calculated by statistical methods. Other properties are related to strength through correlations which may be project specific or generalised. Recognised standards have been established that define the degree of quality control from excellent to poor based on statistical results.

Quality control has important economic value. For the construction staff, consistent batch-to-batch uniformity means dependable fresh concrete with the desired placement properties including workability, response to consolidation, finishing properties and surface appearance. Nothing is more disruptive to a well executed placement than frequent changes in consistency or workability caused by lack of control. Such conditions usually result in interruptions, inefficiency and delay to the work while efforts are made to correct the problems. Furthermore, providing a well-controlled product enables concrete mixture management wherein the content of cement and pozzolan can be optimised to reduce cost. The reduction of a few kilos of cement and pozzolan over the course of a large volume project can have significant cost savings and can be expected to pay for the implementation of a good quality control program.

Quality control assures the Owner that the product he receives (and pays for) satisfies the technical requirements of the specifications and thus should perform as intended over the service life of the project. It also provides documentation of the work should it be necessary to modify any of the project structures or features at some later date.

## 2.3. PURPOSE OF QUALITY ASSURANCE

The purpose of quality assurance is to ensure that all aspects that may affect the properties of the completed works conform to the appropriate quality standards and that this conformance is documented.

Quality assurance is essential in the pre-construction phase of project development. Verification is required that the design and specification can yield a construction suited to its purpose. It takes the form of review of design concepts and detailed designs including technical soundness, cost optimisation and constructability. The appropriateness of the specifications for the intended works, form of contract and construction environment is addressed. In this context “ construction environment ” includes the physical environment of the site, logistics aspects, experience of the Contractors and political circumstances that might impact the construction or the contractual arrangements. The quality assurance programme up to completion of the works should be defined and embodied in the specification.

## 2.4. DEVELOPMENT OF SPECIFICATIONS FROM FEASIBILITY STAGE TO CONSTRUCTION

The development of specifications begins in the early or feasibility study stages of a project when basic decisions are made regarding the type and size of structures and the availability of construction materials to build such structures. For concrete structures where up to 85 percent of the concrete ingredients consist of aggregates, an economical aggregate source with sufficient volume must be identified. A minimum amount of exploration and testing of representative samples must then be performed to determine the nature and quality of aggregate available from the source. Potential sources of cement and pozzolan must also be identified. This information is then used to formulate, based on experience, concrete mixtures that meet typical strength requirements so that cost estimates can be made. Factual information in the early stages can be minimal and good judgement and experience are essential.

As the project moves through the design stages, more information specific to the project is needed on the aggregate source(s) and properties of the concrete made with it. This work should be initiated as early as possible in the design stage because of the time needed to determine aggregate properties, to prepare concrete mixtures and to develop time-dependent data on strength, thermal properties and other engineering properties needed for final design.

If the proposed aggregate source is undeveloped quarry rock, then a test blast and evaluation should be made. Aggregate should then be manufactured from the test blast material into the selected size ranges, preferably in a suitable commercial crushing and screening plant. This operation is usually the most difficult and expensive as most commercial aggregate crushing and screening plants typically do not produce the sizes of aggregate used in construction of dams. Considerable quantities of rock from a test blast may be required to yield representative material, maybe as much as 50 tonnes or more. Care needs to be taken to assure that the particle shape of the manufactured material will be typical of that to be expected during construction. Impact-type crushers typically provide the preferred more cubic particle shape than cone crushers. For large projects these efforts may be warranted and should be implemented, but for smaller projects the effort involved may at times be disproportionate to the benefit, particularly with respect to crushing to the correct particle shape. In these cases concrete trial mixes may have to be made with aggregate which differs from that to be used in production. The finetuning of the mixes made when the Contractor's concrete manufacturing is in place may then lead to larger changes in mix designs than would otherwise be the case. The risk of technical and contractual impacts will then be increased.

If the aggregate source is a natural sand, gravel and cobble deposit, exploration and grading analysis is extremely important to confirm that the required quantity of larger particles for the mass concrete work are present. Smaller sizes can always be manufactured by crushing oversize material if needed, but costs will increase.

Once sufficient aggregate is available from exploration work, this aggregate should be tested for quality and properties needed for preparation of concrete mixtures. Samples of cement and pozzolanic material should be obtained from the most likely sources and tested for compliance with selected standards. Admixtures which may be required should be checked for efficacy in the trial mixes.

Laboratory concrete trial mixtures should then be prepared, covering the strength requirements and required maximum aggregate sizes in accordance with the structural design. Those mixtures to be used in mass concrete work should include specimens and tests for thermal and engineering properties. In many cases laboratory concrete trial mixes are made only after the start of construction. These trials are necessary as only then will the aggregate to be used in construction be available and refinement of the design mixes made possible. However, the results may come too late to be useful in the development of the design and specification of the project. Pre-tender testing should be done whenever possible and should always be done for large projects and where marginal or unusual aggregate has to be used.

The data generated from the program described above provide the information required to define the specification provisions. This information also provides the basis for calculating quantities and bidding the required concrete work.

Completion of the technical specifications is the final task during the tender design stage. The specifications should incorporate all provisions needed to achieve the desired quality in the various portions of the work based on materials meeting the specified requirements, and the required strength and durability of the final product. The specifications can include detailed requirements on the Contractor's aggregate and concrete batching/mixing plants; handling and storage of materials; concrete mixtures and properties; formwork and reinforcement; temperature control measures; transporting, placing, consolidating, finishing, and curing concrete; and foundation and construction joint treatment. How this is done is described in Section 2.5, *Approaches to the Specification of Concrete.*

Verification of compliance of the plants and concrete mixture designs is required as early as possible in the construction phase such that any adjustments or modifications can be made in a timely manner.

## 2.5. APPROACHES TO SPECIFICATION OF CONCRETE

A *method specification* and a *performance specification* are the two basic approaches to specifying the work.

The *method specification* will contain detailed descriptions of all the processes and methods the Contractor must follow in the construction. In the extreme form of this specification the Contractor will supply all equipment and labour specified and will follow the prescribed procedures for manufacture and construction. The Contractor thus has limited responsibility and limited opportunity for optimising the cost and time of construction. The quality of the end product is given by prescribed procedures and is therefore largely the responsibility of the Designer and Owner.

In contrast to this, the *performance specification* provides a description of the required products, leaving the methods required to achieve this to the Contractor. This type of specification shifts the responsibility for quality towards the Contractor. It gives the Contractor the opportunity to install efficient construction processes based on his experience and available equipment. The influence and control of the Designer on the construction is reduced as is his responsibility for quality control. In extreme forms of such contracts the Project Manager or Designer may be responsible only for quality assurance. A turnkey or EPC (Engineering, Procurement, Construction) contract would typically fall into this last category.

Specifications can contain elements of both approaches. The best balance between the elements depends on a number of factors which may include the size and complexity of the work, the experience of the Contractor and of the Designer, and the construction environment (c.f. Section 2.3).

The experience of the Contractor who will execute the works is of course not known prior to tender, but a pre-qualification process and a short-list of approved tenderers may give some assurance of having a qualified Contractor for construction. In general, where a very experienced Contractor is expected or necessary, the specification can be biased towards performance requirements. With less experienced Contractors the construction means and methods may have to be prescribed in greater detail. The knowledge and experience of the Designer then becomes vital in providing a practical and appropriate specification. If the Designer fails in this respect, claims from the Contractor may be the result and quality goals may not be achieved. Specifications which are basically of the performance type, commonly have methods described in addition, particularly where such methods are held to be an integral part of the design. The designer may be prudent in allowing tenderers to propose alternatives to the prescribed methods where these may yield sound results.

Where a performance specification is provided, the concrete must not be specified in terms of strength alone. Other matters of consequence to the design such as density, durability, maximum allowable temperature and water-tightness are important. The proportions of concrete mixes are commonly developed as part of the design and may be specified subject to changes and adjustments required as a result of field experience.

In method specifications, the Owner’s Representative, usually the Designer, assumes responsibility for the concrete mixtures used in the work and the results obtained. It is important in this approach that cement and pozzolan be paid as separate items from concrete to allow flexibility in mixture adjustments. The Owner’s Representative is also responsible for quality control including testing and inspection. The Contractor is required to provide the materials and equipment, and to perform the work as specified. His responsibilities include any labour and facilities needed for obtaining representative samples of materials and fresh concrete and delivering these samples to the engineer for testing. This approach generally requires the Owner to provide a large organisation to perform the testing, inspection, and other quality control tasks. If the specification is well written and appropriate for the work, materials are uniform, concrete mixtures are properly proportioned to meet design requirements, and provisions regarding concrete production and placement are enforced by a well trained, experienced, and dedicated inspection force, then there is no reason to believe that anything other than a quality product will result. Testing will only confirm that all of these activities were properly performed and controlled.

The current trend in the construction industry is towards the performance approach to specifications. With this approach the Contractor is responsible for the concrete mixtures, for quality control, and for overall quality of the completed work. Accordingly, specification provisions must be expanded to detail the required quality control organisation, qualifications of personnel, inspections to be performed, authority, facilities, equipment, reporting procedures, and documentation. Specification provisions on concrete mixtures must also be expanded to define required performance parameters that mixtures must satisfy. Furthermore, specifications must clearly state what tests will be made, standards to be followed, frequency of each test, and action to be taken if results do not comply with specified limits. The Owner's representative is responsible only for quality assurance. Quality assurance activities include closely monitoring the Contractor's quality control program and a minimum amount of acceptance testing. Acceptance testing usually consists of about 10 % of the quality control testing performed by the Contractor. The Contractor's laboratory and equipment are usually used for the quality assurance testing to avoid duplicating facilities. Accordingly, the Owner's representative staff is much smaller.

While there may be some disagreement, it is generally accepted that method specifications produce the best quality work for large dam projects. Typically the design and specification for the dam will be provided by an experienced company, whereas the construction may on occasion be made by a Contractor with little experience of dams. This may be reflected in the Contractor's understanding of requirements of concrete. Contractors may be biased more towards profit and might place less emphasis on the balance of properties of hardened concrete. Furthermore, when the Owner's representative is responsible for concrete mixtures, it is more likely that cement and pozzolan contents will be optimised to achieve cost benefits, and thermal characteristic and engineering properties will be better controlled. This is all contingent upon the Designer having a high level of technical expertise. Sometimes the Contractor will have the knowledge and experience to produce the best mix designs. In countries with a uniform and strong engineering culture with high standards of design and construction, provision of a performance specification may be the preferred option.

## 2.6. APPROACHES TO QUALITY CONTROL, DIVISION OF RESPONSIBILITIES

Up to the time a contract for construction has been awarded, the specifications and quality control provisions are the sole responsibility of the Designer. The responsibility for the various quality aspects from the time a contract has been awarded will depend on the nature of the contract, conventional or turnkey/EPC, as illustrated in Fig. 1 and 2.

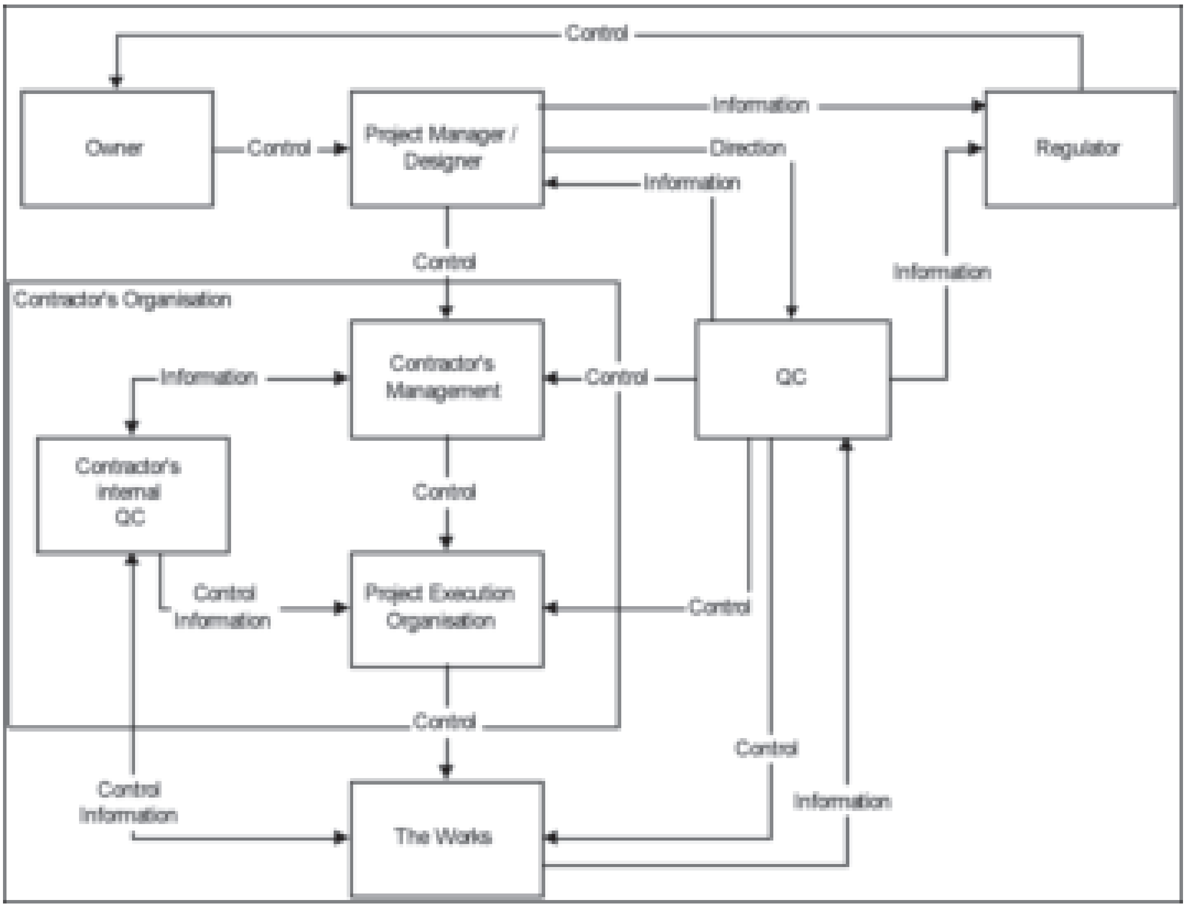

Fig 1
Typical QC system for a conventional construction contract

It is important that the specifications and quality control provisions are reviewed carefully for appropriateness and completeness by all parties involved in the design, including the Owner and regulating agencies. The responsibilities for all aspects of the work must be clearly defined. Any questions on the specified provisions must be satisfied. Quality control of the quality control documentation is of great importance.

More than one party will typically be engaged in quality control on a major project. Parties that may be involved can be the Owner with his Project Manager or Designer, the financing institutions, the Contractor, an independent quality control specialist and regulating agencies.

The Contractor will always provide his own quality control system. To control concrete manufacturing, transport and placement he has a need for extensive testing and quality evaluation in order to satisfy specifications and achieve the required end result. He needs testing information in commissioning and running his manufacturing facility.

Quality control required for verification may reside with the Project Manager or Designer, the Contractor or may be an independent third party. If the Contractor provides quality control services under his main contract, the Owner (or one of his agents) may provide only limited quality control and quality assurance using his own staff or a hired specialist company to obtain further corroboration.

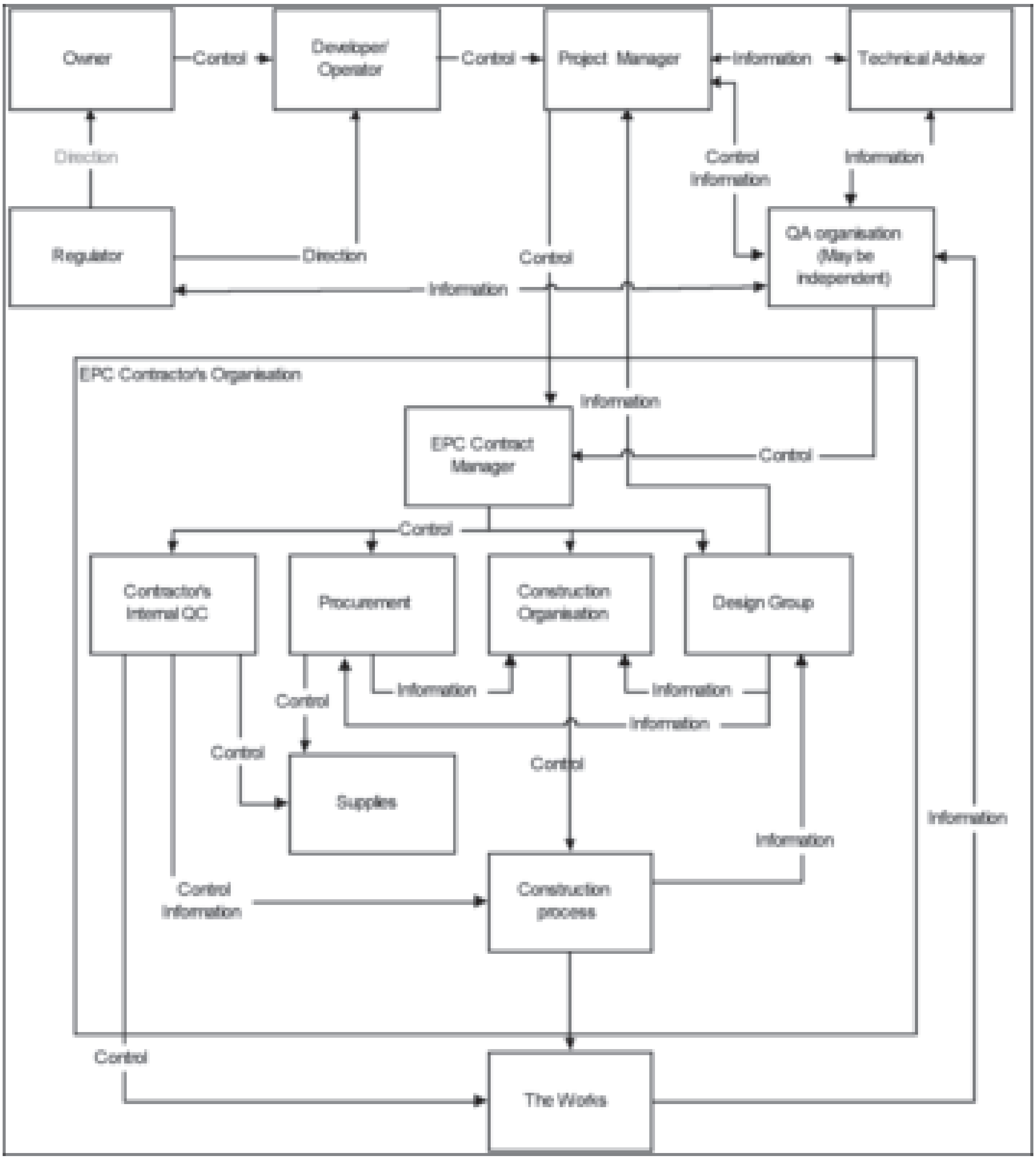

Fig. 2
Typical QC system for an EPC construction contract

The apportionment of responsibility for quality control will depend to a large extent on the type of contract (conventional re-measurement or turnkey) and the type of specification (method or performance). A method specification will place the least responsibility on the Contractor as the Designer takes charge of all quality control, verification testing and inspection. The Contractor would still carry out testing for his own information and control. At the other extreme the Contractor takes over all quality control functions under a turnkey or EPC contract. The Designer or Owner's Representative is responsible for quality assurance in all cases although the Contractor may have quality assurance routines in place for his own internal purposes.

Regulating agencies, who are normally concerned with dam safety and societal risk, are often required to provide separate quality control of the dam construction. This is typically more a quality assurance activity, but some agencies provide their own on-site inspection and may take physical samples for periodic testing. Regulating agencies will rely on the Contractor's or Owner's quality control testing, may provide limited independent corroboration, and will make their own assessment of the adequacy of the construction.

## 2.7. REQUIREMENTS FOR EFFECTIVE QUALITY CONTROL

Quality of construction cannot be obtained without knowledgeable and well-trained construction staff including equipment operators and labour. A pre-condition for successful construction is that core staff on the site has appropriate experience. A large number of personnel have to be engaged for a major project. These will require training for their various tasks to ensure that their work conforms to the specifications and good practice. Training for everyone is needed to ensure familiarity with the systems needed to ensure effective and quality construction. This all applies to construction leaders and operators as well as quality control inspectors, laboratory technicians and their leaders.

Plans for training of the Contractor's staff should be in place at the commencement of construction. Some training will be in the form of lectures and meetings. Other will be practical training relating to concrete manufacture and placement. Training in effective and timely communication should be part of the training plan. Practical training grounds can be temporary works or non-critical structures where concreting and quality control can be taught and practiced.

At this stage effective communications between the parties, particularly between the Owner's quality control organisation and the construction team, should be established and tested. This applies to immediate, verbal communication as well as formal notifications. Any cultural reluctance to direct or comment on other's work should be overcome as part of the training exercise: a common understanding should be developed of the importance of each person's roll in the success of the project.

Effective quality control requires the following:

- A good management structure is essential. Responsibilities have to be well defined. There should be no inherent conflicts of interest.
- The quality control team requires powers to control the quality of the work. This may include powers to reject and remove deficient materials and products. In turnkey and EPC contracts the independence of the quality control organisation should be safeguarded. The Owner's quality assurance programme becomes particularly important in this context.
- There has to be unity of purpose among all the persons contributing to the construction as well as the stakeholders. This requires a commitment to quality from the construction manager and the whole construction team as well as QC.
- The personnel in the QC team have to be suitably qualified and trained for the activities at hand.

- The quality standards have to be clear through the design documentation including specifications. The standards and codes of practice have to be appropriate and properly understood.
- Appropriate and sufficient office, laboratory and field facilities have to be provided.
- Effective communication, with respect to precision and timeliness, is essential to achieving a good quality and serviceable end product. Communications should be immediate and directly between the active parties across the boundaries of the respective organisations. A hierarchical system of communication is not suitable for day-to-day quality control communications.
- An effective system of document control is required.

Careful planning and adequate financing is necessary to achieve the above. Personnel central to the organisation should be in place as early as possible such that they can develop the QC team and have it fully functional when its services are required.

As stated above, a pre-requisite for achieving quality is a design and a specification suited to the work at hand. Good quality also demands Designers and Contractors with proven abilities. *Quality is designed into the works. Good quality cannot be obtained by testing alone: poorly designed or poorly specified works will remain of poor quality whatever quality control system is devised and implemented.*

## 2.8. SOURCES OF PROBLEMS AND ERROR AVOIDANCE

During construction, problems can arise from errors in the technical specifications and quality control program. The most frequent error is specifying standards and codes that are not appropriate or not sufficiently specific for the particular application. Care must be taken in preparation of the technical specifications to re-examine standards and codes that may be contained in any guide specification or previous project specification used as a model. Standards and codes should be current and applicable to the work and project site. Where standards contain several options, the appropriate option should be stated so that there is no confusion about which option applies to the work.

Specification provisions must be suited to the local conditions and skill of the labour. Care should be taken to avoid requiring a restrictive tolerance that cannot be reasonably or practically achieved under site conditions. Examples are overly stringent placement or joint grouting temperatures, unreasonably low specified differences in height between adjacent blocks in arch or gravity dams, or frost resistance requirement for a downstream facing concrete for dams in frost-free regions.

# 3. CONCRETE CONSTITUENTS AND CONCRETE MANUFACTURE

## 3.1. MATERIAL SPECIFICATION AND CONTROL

### 3.1.1. Introduction

The technical specifications for concrete for dams typically deal with several aspects:

1. The properties of the hardened concrete to accord with design requirements. These properties will include strength, unit weight and durability. The finish (smoothness) required is affected by the concrete properties and is very important for hydraulic surfaces such as spillways.
2. The properties of the constituent materials of the concrete: aggregate, cement, pozzolan, water, ice and chemical admixtures and the temperatures of all of these.
3. The proportions of the constituent materials.
4. The concrete manufacturing process: aggregate production, storage, batching, mixing, transport, placing, finishing and curing.
5. Properties of the fresh concrete: workability, segregation, bleed, uniformity and temperature.
6. Workmanship and good practice.

The objective of the material specification and control is to ensure that all materials have desirable properties and reducing variations in these, all to ensure adequate concrete strength with minimal variations.

In principle, specifications for hardened concrete could be sufficient to produce the required result. This may be feasible for small works, but not for dams where large quantities are involved and where placement rates are high. Typically, concrete for dams has to be approved based on its constituents, the properties of the fresh concrete and placement procedures with correlations between these factors and long-term strength gain. Prior to going to tender, normally the Designers will have carried out a testing program. Data so derived, with experience from other dams, will allow determination of the quantities and procedures required to make such approval possible. Optimisation of concrete properties and reduction of cost are further important objectives. This information is then embodied in the specification (points 2 to 5 above).

Consistency of the properties of materials making up the concrete with the manufacturing and placement processes are essential to producing hardened concrete with consistent properties.

The specification and testing of the above aspects are often based on compliance with internationally used standards such as ASTM, ACI, BS or EU. Where more subjective judgement is involved (workmanship, finishing) common sense, experience or peer review should suffice.

### 3.1.2. Aggregate

*Sampling*

Representative samples have to be obtained from various points in the aggregate production plant. Samples are obtained from the production stream by the means of mechanical samplers located on transport belts or chutes. If production can be interrupted briefly, then samples can be taken from the same locations without the assistance of a mechanical sampler. Sampling stockpiles is often not satisfactory because of segregation on the pile exteriors and because stockpile samples do not necessarily reflect current production.

*Typical tests*

The following tests are commonly used to control aggregate quality:

Table 1
Typical tests for aggregate

| **Quarry or borrow pit** | | |
|---|---|---|
| Petrography | Specific weight | Sulphides |
| Compressive strength | Absorption | Chloride |
| Soundness | Alkali-aggregate reactivity | Organic matter |
| Abrasion resistance | Sulphates | Mica, Clay |
| **Product streams** | | |
| Grading | Particle shape | |
| **Before loading into or in batch plant bins** | | |
| Grading | Absorption | |
| Moisture content | Temperature | |

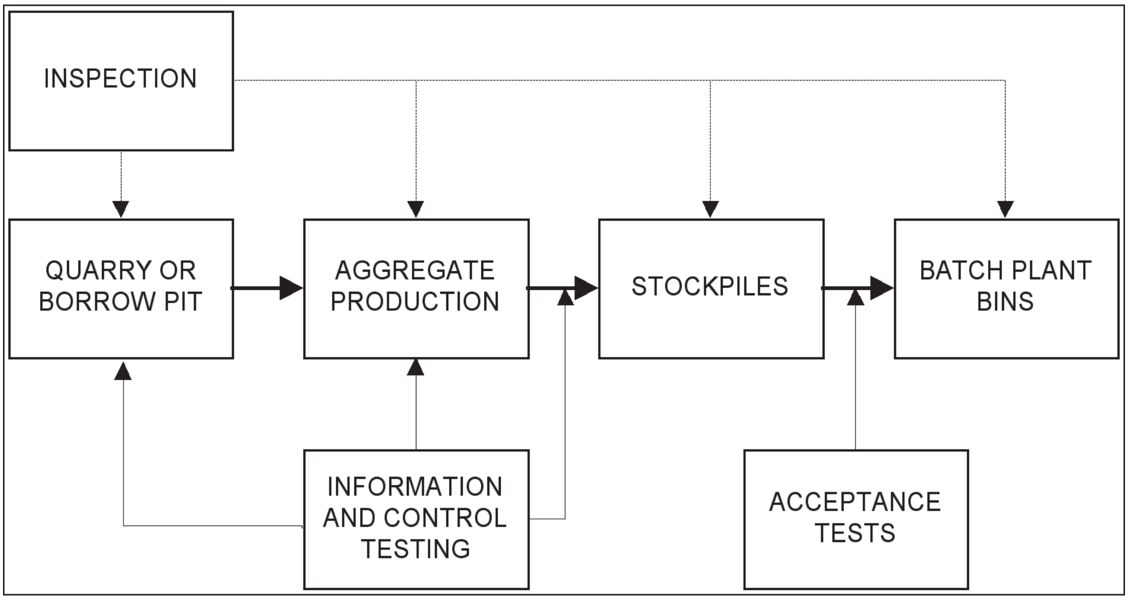

Fig. 3
Quality control of aggregate production

### *Aggregate quality*

Aggregate is normally derived from local sources to avoid the considerable cost attached to transport. Some sources will yield aggregate of high quality which conforms to national or international standards. Others may be sub-standard in one or more ways. Specification of processes and concrete mixtures can overcome such defects and produce adequate concrete.

Where the aggregate source is known to be of good quality, the specification can be based on published standards such as ACI 221 or ASTM C-33.

The physical properties of the rock in the quarry or borrow area are normally measured in the design phase. Tests are carried out to determine rock types, strengths, gradings, particle shapes, temperatures, modulus, thermal properties, freeze-thaw resistance, abrasion resistance, specific gravity, porosity, water absorption, moisture content and the content of impurities. The chemical soundness of the rock is also investigated and includes tests for alkali-silica reaction (ASR), sulphate resistance and other issues. Some of these tests may be carried out during construction to ensure that the source material and the aggregate produced conform to the design assumptions as embodied in the specifications. Test frequencies will depend on the consistency of the source.

In some quarries more than one rock type is present and some material on its own might not conform to specified standards, but might do so when blended with better rock.

### *Poor or variable sources*

Aggregate derived from poorer and variable sources require particular specification that may differ from standards in various respects. Aggregate soundness, particle shape, absorption and the presence of deleterious substances and reactive minerals may have to be dealt with both with respect to quantity and allowable variation. Aggregate that does not conform to proven standards may have consequences for aggregate processing and transport as well as the proportions of the concrete mixture with admixtures. The use of weak aggregates should not be eliminated just because some properties do not comply with common practice or established standards. Essential for the acceptance of such marginal material is an extensive test program. It is evident that marginal material needs testing of the product in which it is used (concrete) in addition to testing the aggregate parameters. Without an intensive test program it would be irresponsible to accept such material.

Some aggregate may give excessive breakage of particles during handling or because of time-dependent climatic deterioration that will change the gradation and produce fines. To some extent, this can be accommodated by re-screening and possibly washing prior to batching. Some aggregate sources yield flaky and elongated particles. Particle shape can be modified during aggregate processing by introducing particular crushers and by crusher adjustment. The required mortar and cementitious material contents may increase if aggregate with poor particle shape is used, with attendant consequences for temperature rise, shrinkage, cracking potential and cost.

Mixtures of hard and soft alluvial gravel have been used as an aggregate source in some circumstances. Crushing may reduce the unsuitable soft material to a fine fraction that can be removed by screening and washing. Further crushing of the harder material can then yield usable aggregate.

*Aggregate grading*

The specification will typically include required grading bands for each aggregate size and possibly composite gradations after batching. These gradations may be taken from codes and formulas or may be derived or modified by testing. Initially, the allowable gradation bands may be relatively broad and consideration may be given to reducing the allowable variation once the manufacturing process has commenced. In this context the composite gradation is important. The number of aggregate sizes will affect the possibility of maintaining the composite gradation within tight limits, even with considerable variation in the gradation of each aggregate size. Up to six sizes (including two of fine aggregate) may be used to achieve a high level of control. Re-screening of coarse aggregates above the batching station bins can assure optimum gradation of the produced concrete by removal of excess fines created during transfer of aggregates from crushing and screening plant to the concrete plant.

*Reactive aggregate*

Where tests have shown that aggregate may react chemically with the cement, measures have to be taken to ensure that deleterious effects will not occur. Normally these measures include a requirement for use of a pozzolan in the concrete and the use of low alkali or sulphate resistant cement, depending on the nature of the problem. Pozzolan is also commonly required to reduce heat gain, improve workability and reduce permeability and cost. Where pozzolans are not economically available, the inclusion of measured quantities of crusher dust from particular rock types can sometimes have the same effect. Tests are required prior to construction to ensure that pozzolans or other added materials can yield the required properties. Consideration should be given to carrying out the more definitive concrete and mortar bar tests in addition to the conventional and more rapid petrographic and chemical tests.

*Moisture content of aggregate*

The water content of the aggregate has to be consistent. To avoid problems with slump loss due to absorption of water into the aggregate between mixing and placement, the coarse aggregate has to be surface saturated and of consistent free water content. This can be achieved by appropriate stockpile management, which may include keeping the coarse aggregate wet by watering. The use of wet-belts, primarily for cooling purposes, and final screening before deposition in the batch bins, can yield aggregate with consistent moisture. Fine aggregate commonly contains free water because it drains slowly. Again, good stockpile management (consistent time between processing and use, consistent handling procedures) helps to reduce the variation in free water content.

### 3.1.3. Cementitious materials

Standards for cement from countries with well-developed cement industries work well for the context for which they were developed. Such standards are commonly based on physical properties (fineness), restrictions on the quantities of certain chemicals and the specification of minimum paste strengths after given curing times and setting times. Variations in properties can be considerable even if commonly used standards for these materials are met. Specification of cement by reference to such standards may not be sufficient where locally produced cements are variable or at the margins of normally accepted standards, often because of poor access to consistent raw materials. This applies to the sources of silica, limestone and gypsum. Changes in gypsum sources have been known to dramatically affect setting times without any obvious changes in the chemical composition. Further specification may be required to ensure a consistent product, such as specifying the acceptable range of tri-calcium silicate. Without such additional specification and attendant controls, the properties of fresh and hardened concrete can be variable and difficult to control. Manufacturers have on occasion compensated for poor properties by increasing the fineness of the cement in order to achieve the standard specified early strength. On small projects, and on some quite large ones, the cement supplier may not be interested in modifying his product. Design may have to be made with acknowledgement of variability of the cement.

Most important is the control of uniformity, which can vary considerably due to heterogeneous sources or caused by the grinding process (fineness). This calls for a quality history report of the mineral admixture (statistical record), e.g. by a long-term, plant-specific certification of fly ashes.

The maximum allowable temperature at arrival on site and the maximum age of cement since manufacture are normally specified. The use of hot cement is undesirable as it raises the temperature of the concrete. Cooling of cement with liquid nitrogen can be done, but is expensive. Chilled dry air has been used as a cheaper alternative and to good effect. If cement temperature may be a problem, these factors must be addressed in the concrete mix design and the specification. Cement loses its reactivity with age and is prohibited from use after a certain time by most codes of practice.

The rate of cement consumption can be very high for large dams and the turnover of on-site storage can be rapid. A full set of tests to verify cement composition and physical properties at site can often not be done before the cement is used. Considerable reliance has to be placed on the manufacturer's certificates. In the early phases of construction, it may be prudent to arrange for comprehensive testing of the cement at an independent laboratory at frequent intervals until there is full confidence in the manufacturer's test results. After that, such tests should be carried out periodically. The tests that can realistically be performed at site are related to setting time and temperature. Fig. 4 shows schematically a typical cement production and control system.

On some large dam projects, silos at the cement works have been rented and dedicated to the project and these silos have been filled only with approved cement and all cement used in the project has been drawn from these silos. This can go a long way towards ensuring that only acceptable cement is transported to the project site.

### *Mineral Admixtures*

The most common type of mineral admixture used in dam concrete is pozzolan derived either from natural sources or industry. Of the latter, fly-ash from coal-

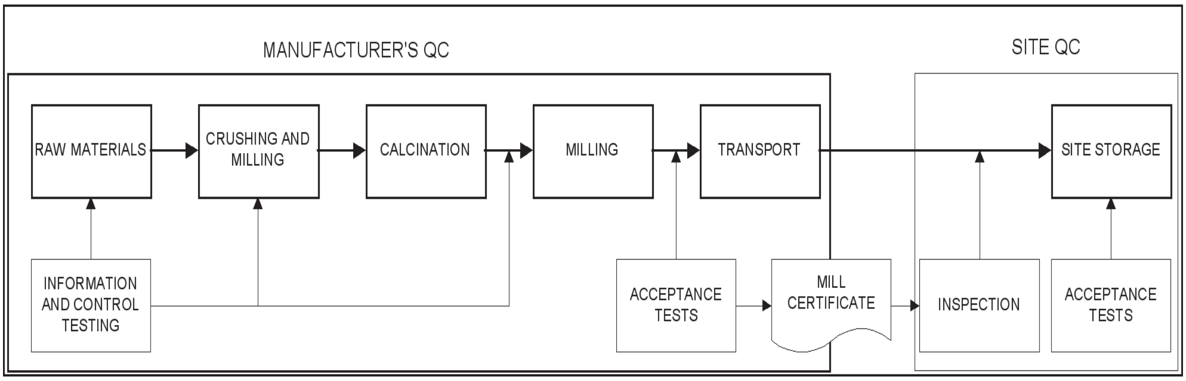

Fig. 4
Schematic diagram of quality control of cement

burning power stations or blast furnace slag are the most common. Silica fume is also used for concrete, particularly when high strength concrete is required. The effectiveness of pozzolans from possible sources has to be tested with the particular cement or cements to be used. Changes in pozzolan composition can affect concrete properties such as producing variable workability.

The properties of fly-ash can vary from power station to power station and from coal source to coal source and is also dependent on the source of coal. It can also vary within a power station depending upon the equipment used to mill the coal and occasionally on the boiler furnace. A reasonably consistent product can usually be obtained by sourcing fly-ash from a particular power station with a consistent and uniform source of coal. Consideration should be given to including such restrictions in the specification. If these conditions are met, the power station still has to operate in a uniform and consistent manner to achieve a consistent fly-ash and the collection of the ash has to be made from a particular precipitator. A number of standards give different requirements for the chemical and physical properties of fly-ash. Some properties, however, are not always achieved. Notable is the carbon content, which may exceed standard limits. Although a variable carbon content may affect concrete water demand and workability, it may be acceptable to exceed these limits provided the range of variation is kept small. This should be verified through pre-construction mix design testing. Consistent fineness is also important and can be easily and quickly tested by the site laboratory. Varying fineness will have an adverse effect on concrete workability, particularly with RCC. The particle shape of the fly ash can affect the workability of the concrete with non-spheroidal material having a high water demand which results in lower workability, especially with RCC.

### 3.1.4. Chemical Admixtures

A number of chemical admixtures are available to improve the properties of fresh concrete. Admixtures commonly used in dam concrete are set retarders and water reducing / workability enhancing chemicals and air-entraining agents. Admixtures are available that combine more than one of these properties.

Water reducing agents are often used for mass concrete mixes with poor workability. Set retarders also have their place in some circumstances. They have been used in roller-compacted concrete (RCC) to lengthen the setting time and thus improve the bond between successive concrete lifts. There may be a need to adjust the amount of set retarder and possibly other agents used in the concrete in response to seasonal temperature changes.

Air entrainment admixtures are commonly specified. They have the effect of improving workability, reducing water demand and bleed and improving frost resistance. These agents can yield indifferent to poor results with some concrete mixtures with high pozzolan contents.

Chemical admixtures can be expensive and their use should be limited to situations where they are necessary to achieving good quality concrete and where this is the most economic option.

The effects of admixtures have to be tested with the various concrete mixes. These tests are typical setting times and workability (slump test or loaded VeBe test). Poor or undesirable results can arise with particular products because of incompatibility with cement or pozzolan and with some types of aggregates and may also arise with seasonal variations in air temperature. These cases may require a change of type or brand of admixture. Such tests should be carried out periodically throughout the construction period.

### 3.1.5. Water and ice

Water quality for concrete mixing should satisfy an appropriate standard with respect to the content of contaminants. Potable water is preferred for mass concrete as it has typically been filtered for contaminants. When potable water is not available, tests should be made with the precise source of construction water to validate the mix design and concrete properties.

Mixing water may have to be cooled or heated to regulate the concrete temperature. Some or much of the mixing water may be replaced by flake ice when concreting in hot climates. A maximum ice temperature may be specified.

## 3.2. TRIAL MIX PROGRAMMES

The trial mix programme is designed to test and select the mix proportions, which will give concrete of the desired fresh and hardened properties. The programme made in the design phase should be subject to quality control and assurance. Identification of appropriate testing standards and quality assurance with respect to the balance of fresh and hardened properties is required. The programme carried out in the construction phase will require quality control and assurance dependent on whether the Designer or Contractor is responsible for the mix designs. Where the Contractor is responsible for the mix designs, the specification may include requirements on:

- Procedures used to develop the mix designs
- Design strength of the concrete at a given maturity
- Maximum size of aggregate (MSA)
- The number of aggregate sizes to be batched for each MSA
- Limits on the combined aggregate grading for each MSA

- Maximum water-cement ratios
- Air entrainment
- Minimum cement or cementitious contents (in relation to durability, watertightness or other factors)
- Minimum proportion of pozzolan required in the mix in order to mitigate the risk of alkali-silica reaction (ASR)
- Minimum density for RCC, typically as a percentage of Theoretical Air-Free Density (TAFD)
- Workability, such as slump or VeBe time (RCC)
- The method of determining the target strength of the concrete as a function of the design strength and expected statistical variations in strength
- Temperature at the time of placement or completion of mixing
- Sample curing procedure and temperature
- The maturities at which specimens are to be tested which may range from the 3-day to 365-day strengths and sometimes more, depending on the particular application. In some instances, early age (e.g. one day) strength using hot accelerated curing procedures may also be appropriate.

There will typically be a requirement for testing of cementitious materials from each source which may be used and for each combination of material sources which may be employed.

Where the Designer is responsible for mix designs, the same items should be addressed in its test programme documentation.

The design strength at a given maturity is commonly given as the crushing strength of either cubes (EN and BS) or cylinders (ASTM). In addition there may be requirements to demonstrate the tensile and shear strength of adopted mixes. The crushing strength is generally used for routine quality control, see Section 5.

The test results will show the rate of strength development with time. This data may be useful in assessing the longer term strength of a production concrete from early test data.

## 3.3. FULL SCALE TRIALS

For large projects, or where there is an inexperienced Contractor, a full-scale trial, or series of trials, is essential. Ideally the full-scale trial should not be used for commissioning of plant; all equipment should be proved and tested prior to the start of the trial.

The trial can have several objectives, amongst these can be:

- the training of personnel, both those working on the dam and also those supervising and inspecting
- the optimisation of the workability and mixture proportions of the concrete
- the optimisation of the construction procedures during the transportation, dumping, compaction and curing of the concrete and also the procedures for

placing the concrete against the upstream and downstream formwork and against a rock abutment

- in RCC dams, a review of the various joint treatments to be used between the layers for various exposure times
- the optimisation of the testing methods for workability and fresh density and for in-situ density.

Some period after the full-scale trial has been completed, cores can be taken from the trial to validate the design assumptions and performance of the Contractor during the trial.

By the end of the trial there should be sufficient operators and supervisors with the necessary skills to place the required concrete in the dam body itself; the first concrete in the dam frequently being the most important to be placed as it can be in the bottom of the structure.

## 3.4. PROCESS SPECIFICATION AND CONTROL

### 3.4.1. Stockpiles and silo storage

Given aggregate and cementitious materials that conform to specification, large stockpiles aid quality. Short-term deviations from specification in aggregate production tend to be evened out. Good stockpile management will reduce the effects of segregation. The time-lag between production and incorporation into concrete allows corrections to be made, such as removal of unsuitable material generated by equipment failure or other causes. Stockpiles of fine aggregate allow these to drain before use.

Continuous concrete production is necessary in many cases for large dam projects, particularly for RCC, in order to achieve a good quality end product. Large stockpiles provide a buffer in the event of problems with the aggregate production or supply. In many projects, the minimum size of stockpile at the commencement of concrete operations is specified for each aggregate gradation. A different and smaller minimum stockpile size may be required during subsequent concrete operations.

Contamination from adjacent material, surfaces, processes and cooling water has to be avoided. Reclaim tunnels may be located at ground level instead of buried and this can reduce the risk of flooding of the reclaim belts. Layout of aggregate stockpiles and cement silos must be studied carefully. Poorly designed facilities of this kind may lead to the requirement for re-washing and re-grading aggregates before transportation to batching bins.

Cooling of the aggregate and prevention of heat gain can be important. In climates with cold winters, aggregate produced in that season will be cold, which may alleviate concrete heat problems or reduce the need for expensive cooling measures. In hot climates, some cooling may be achieved by shading and watering (for evaporative cooling), but further cooling of aggregate is commonly required. Aggregate cooling methods may be cold water immersion, wet-belts and cold air circulated through the concrete plant bins.

Cementitious materials are stored in closed metal silos whenever possible. Bagged cement, and sometimes bagged fly-ash, is used on some projects, but these materials should be transferred to silos upon demand to allow automated batching and give better control of cement usage and rotation of stock.

Quantities of all materials in stockpiles, including water and ice, should be monitored as part of the quality control effort and checked against projected concrete production to ensure that no untimely shortfalls occur.

All layouts, process diagrams and equipment specifications should be provided by the Contractor and approved by the Owner's Representative before any site mobilization related to main concrete works.

### 3.4.2. Quality of manufacturing facility

Good control is contingent upon having concrete manufacturing facilities of high quality with proven capability of giving consistent constituent materials, batching and mixing. Good quality control procedures are in themselves not enough. The cost of providing the equipment to achieve this is high, but on larger projects this cost is recouped through savings in cement and pozzolan consumption and more effective and predictable concrete placements. On smaller projects such investments may not be justifiable as the savings would not cover their cost.

The Owner's Representative needs to specify the equipment to be used in each case either by type or required performance and the equipment should be subject to approval prior to installation.

### 3.4.3. Batching, charging and mixing, Process equipment

The essential functions of the batching, charging and mixing equipment should be specified in the contract documents. The type and capacity of batch plants and mixers are normally given. Equipment which is suited to the type of mixes, the rates of production and quality requirements should be specified. In this context an important quality requirement is a small variation in concrete strength. Different batchers and mixers perform differently in this respect. Accurate batching is essential to producing concrete with consistent fresh and hardened properties. A small variance also has economic consequences as the content of cementitious materials can be reduced while achieving the same design strength, see Chapter 6 (Table 6.2) in ICOLD Bulletin 126 *The State of the art of Roller Compacted Concrete* which provides information on expected variance in strength.

A major source of poor tolerance in batching can be inconsistent time for closure of silo gates. These should close rapidly, at the same rate and the same delay or should allow proportion control, which allows a progressive reduction in aggregate flow. Good preventive maintenance is essential. These issues should be addressed in the specification. Variable water contents, as revealed by workability tests, commonly have their source variations in the moisture content of the fine aggregate. This can be overcome by good stockpile management (consistent watering and drainage) and regular maintenance of moisture probes. The correct function of moisture probes has to be checked by drying samples.

Table 2

Typical quality control activities at concrete batching stations

| **Activity** | **Frequency** |
|---|---|
| Calibration of scales/load cells | Monthly |
| Consistency of gate closures | Monthly |
| Calibration of admixture dispensers | Monthly |
| Calibration of water meters | Monthly |
| Calibration of moisture meters | Weekly |
| Verification of moisture content of fine aggregate | Daily or more frequent |
| Temperature measurement of constituents | Twice daily |
| Verification of batching tolerances | Weekly |
| Verification of maintenance | To follow maintenance schedule |
| Certification of batching station | On installation and then annually |

With modern batching and mixing stations, microprocessor control helps to ensure that batching, charging and mixing are accurate and follows specified procedures. Problems can occur when some part of the system does not function fully as intended and when corrective action is taken by using manual over-rides. Surveillance of the control centre is therefore and essential part of quality control.

Wear of mixer blades will adversely affect the consistency of the concrete mix. Mixer blades must remain within specified tolerances and have to be changed when wear reaches the specified limits.

Table 3

Typical quality control activities at the concrete mixing plant

| **Activity** | **Frequency** |
|---|---|
| Mixer efficiency tests | At start-up, monthly and changes in material sources |
| Mixing times | Each batch |
| Workability | Each batch to hourly (with RCC) |
| Verification of preventive maintenance | To follow the maintenance schedule |
| Cleaning and maintenance | Daily |

The charging sequence will affect how well the concrete is mixed or the duration of mixing required to produce a consistent mixture. The dry materials are normally delivered to the mixer on belts which receive the materials, including cement, simultaneously, thus giving some pre-blending.

Concrete plants with separate single material weigh batchers for each size and type of material provide the optimum mixture design for the concrete, and the minimum cycle time between batches. Also the materials can be pre-blended whilst being transferred from batchers to the mixer, which minimises required time for mixing.

### 3.4.4. Control of water content

A consistent water-cement ratio is crucial to consistent strength. The batch plant must be able to compensate for variations in aggregate moisture content. Rapid variations in moisture content of the fine aggregate make this control difficult and frequent testing may be required. Automatic moisture probes installed in the fine aggregate feed can be used but are not always reliable. The specification should address these issues.

### 3.4.5. Fresh concrete properties and verification

Workability should be checked at the point of discharge from the mixer to the transport belt or truck. Concrete outside the specified tolerances should be discarded and the cause of the non-compliance identified and corrections made. Dispatching out-of-specification concrete from the batching plant should not occur as it disrupts the concreting operation and may affect quality even if the out-of-specification concrete is not used in the pour.

The consistency of the concrete is normally measured immediately after mixing with the slump test (or loaded VeBe test for the low workability mixes used for RCC) and again at the point of placement. The first test gives an indication that the mix is consistent (and an early warning at the batch plant of errors) and the second test gives a check that the concrete has the correct workability for the method of placement and consolidation. The loss of workability between the two times and places of testing should be consistent.

Because of workability loss during transport, the acceptable workability may be different at the mixer and the point of placement.

Inspection of the concrete and familiarity with its appearance and behaviour are important elements in achieving a consistent product. Rapid and precise communications between the quality control inspectors and the batching and mixing station are essential as changes in the properties of the fresh concrete have to be corrected promptly.

Final acceptance of concrete for placement is normally made based on tests at the point of placement, see Chapters 4 and 5.

# 4. CONTROL OF CONCRETE TRANSPORT AND PLACEMENT

## 4.1. TRANSPORT

### 4.1.1. Specification

Concrete may be transported from the concrete plant to the point of the placement by several means as a function of distance, rate of placement and environmental factors. The method of transport may affect the workability of the concrete and may cause segregation. Transportation and handling equipment should not only have the required capacity but also be capable of being adapted to different mixes and should be designed to minimise segregation. Checks are required to ensure that the method of concrete transport will not adversely affect the fresh concrete properties such as may be induced by drying, wetting or segregation. The specification may simply require a maximum workability loss as the means of controlling drying during transport, account having been taken of workability loss due to water absorption by the aggregate and other causes. A range of acceptable workabilities at the point of placement should normally take care of water gain from rain or other sources. Some specifications will also include requirements for covering open trucks and conveyors to prevent moisture loss or gain and heat gain during transport.

### 4.1.2. Quality control

Quality control is largely confined to inspection and ensuring conformity with the prescribed measures. Procedures have to be established for the cleaning of transit mixers (ready-mix trucks) and other truck carriers between loads. Such procedures will include verification of the absence of cleaning water prior to loading. Maximum transit times are normally given and a continuous check has to be made that these are adhered to, normally by recording the time of delivery on the delivery docket, which should also include the time of mixing.

Maintenance of transport vehicles and conveyor belts has to be carried out and verified. This includes daily maintenance, which entails cleaning off accumulated concrete on the delivery system as well as mechanical maintenance. Failure to carry out such tasks will cause reduced capacity in the system and breakdowns, which can adversely affect the quality of the concrete.

## 4.2. DELIVERY AND PLACEMENT

### 4.2.1. Specification

The specification for delivery and placement will in essence describe good practice which has been established to avoid defects in the placed concrete.

The specification should require the provision of measures which are aimed at preventing segregation during delivery and placements. Factors included are limitations on free drop heights for the concrete, trunking and delivery directly into the final location. Movement of concrete by using poker vibrators is normally prohibited. There may be provision for eliminating segregated concrete by manual or mechanical re-mixing after initial placement. The method of consolidation will be detailed. This may be the size and number of poker vibrators for traditional concrete and the type and size of roller compactors with required numbers of passes for RCC.

For RCC, lift thickness is normally specified as well as the method for ensuring monolithic construction within each lift. The same applies to conventional mass concrete, but here the layer thickness within each lift is also specified. To eliminate the risk of segregation at the base of a lift, particularly with large MSA and lean mass concrete, a bedding mix with a lesser MSA and possibly a higher cementitious content may be required.

Tests for concrete consistency (slump or VeBe test for RCC) as well as concrete temperature at the point of delivery may be required along with acceptance criteria. The acceptance criteria will include allowable variations in measured properties and grounds for rejection of concrete as unsuitable.

### 4.2.2. Inspection

Control of the concrete placement by inspection is essential to ensure that the required end product is achieved. The concrete is normally inspected at the point of delivery to the site and at discharge into the form. Inspection is a visual check on the appearance of the concrete where workability, uniformity and conformity with established appearance are important. Deviations suggest that something is wrong with the mixture and that corrective action is required.

In some circumstances it may be necessary to adjust the workability of concrete at the placement by the addition of water while it is in the transit mixer. This is an acceptable practice providing the specified water-cement ratio and the total allowable water in the mix are not exceeded. However, this adjustment should not be necessary in a well controlled concrete manufacturing process. Unusual loss of workability is commonly a sign of problems in the system or with the materials.

Good communications between the point of placement and the batch plant are essential. Any undesired changes in fresh concrete properties at the placement have to be acted upon and corrections made to the mixture at the batching and mixing plant.

Working procedures have to be followed and verified by the inspectors. Important factors are correct placement procedures (lift thicknesses, set-backs of successive lifts, elimination of rock pockets) and consolidation procedures (depth and time of vibration, uniformity of treatment) and conformity of equipment to specification requirements. Verification of the adequacy of the curing method and time is important.

### 4.2.3. Testing at time of placement

The purpose of routine control tests is to check and confirm the properties of the fresh concrete such as temperature, workability, and air content, and immediately make any adjustments that are necessary. These tests should be run on the first batch out of the plant and randomly during each shift or placement or whenever change is observed in the appearance of the concrete. Inspectors can quickly learn to visually judge the consistency or workability of the concrete as delivered to the placement. These inspectors should be alert to any changes and to notify the batching/mixing plant immediately when concrete characteristics are not as they should be. This requires effective and reliable communications equipment, either radio or landlines.

Testing is performed at time of placement to ensure that the concrete has the appropriate workability, temperature, compacted density and air content. When delivery to the site is by truck, the concrete is commonly tested before it is discharged to avoid the risk of removal of non-conforming concrete from the placement. Workability is measured with the slump test for normal mass concrete. For low workability (zero slump RCC) mixes the Loaded VeBe test is normally employed (other tests are in use in some countries). The Loaded VeBe time also is dependent on the test equipment vibration frequency (function of the site power supply), amplitude and surcharge weight, all should be specified. The testing frequency depends on the mode of delivery and the experienced consistency of concrete properties. Depending on circumstances, and until the consistency of mix properties has been established, it may be necessary to test each concrete truck for slump and temperature. Concrete delivered by conveyor is usually tested at a frequency based on the volume placed or at a timed frequency. Additional tests should be done when visual inspection suggests that the concrete is not conforming to the specification.

Wet sieving of the concrete is occasionally used to verify that the aggregate grading conforms to the specification and provides an indication that the required cementitious content has been attained.

Concrete cylinders or cube test specimens are made for subsequent testing, see Section 5. This testing is for final verification of concrete quality. The test results will be available weeks and months after the concrete has been placed and are therefore not used to control the placement. Although such tests can be useful in some circumstances, concrete approval remains with verification of its constituents, manufacture and fresh properties.

Test specimens should exclude aggregate with a size greater than 1/3 of the specimen diameter or cube dimension. These large particles are removed from the mass concrete by wet sieving when the specimens are cast. There needs to be recognition that removal of large particles is solely for convenience in testing and that the properties of the hardened concrete are not identical to those of the concrete with the large particles removed.

# 5. CONTROL OF STRENGTH

## 5.1. THE BASIS FOR APPROVING DAM CONCRETE

Strength testing is intended to provide verification that the concrete in the dam conforms to the design requirements and is the basis for final acceptance. The properties of fresh concrete are the initial basis for accepting concrete for placement as described in Section 3.1.1.

Hardened concrete may be tested for compressive strength, tensile strength and shear strength as well as other properties related to static and dynamic performance. The strength of concrete is normally specified by its compressive strength at a specific maturity, which is the principal property used in acceptance testing. In the design phase, correlations between compressive strength and other strength properties may have been established either from previous projects or from a project-specific test programme. Although tensile or shear strength may be the critical parameters in the design of a dam, acceptance testing is mostly based on compressive strength because these tests are easily carried out, specimens are cheap to make and the tests are reproducible with a moderate coefficient of variation. Tensile strength has been used as part of the acceptance testing on many large dam projects, but it is not common. If such tests are to be used for acceptance, extra care has to be taken in performing the tests and their number has to be sufficient to make the results statistically significant. The indirect (Brazilian) split tensile strength test is more easily undertaken in a site laboratory and can be correlated to the more complicated and costly direct tensile test.

Strength of concrete depends on ambient conditions and on time and its quality control needs to take into account the influence of these conditions.

Different methods and standards of strength measurement are in use in different countries. For major dams, comparison of concrete properties worldwide is essential in correlating test properties and dam performance. Therefore, specification of testing equipment and sample sizes is also part of quality control. It is also essential not to depart from approved standardised procedures. Measured strengths and other properties will not be the same as in the structure because of the nature of the tests and differences in how the concrete has been affected by its environment in the laboratory and in the prototype. The influence of curing and wet screening of test specimens are examples.

Compressive strength is measured either on cubes (150 mm sides) or cylinders (150 × 300 mm). There is a significant difference in strength as measured by the two methods which must be taken into account in the design and specification. Although these samples sizes are most commonly used for routine testing and quality control, larger test specimen sizes are also in use, for example cubes of 200 × 200 mm and 300 × 300 mm and cylinders of 300 × 450 mm and even larger.

## 5.2. VARIATIONS IN STRENGTH AND STATISTICS

The measured strength of concrete varies because of inevitable variations in material, the concrete proportions, in manufacture, delivery, placement and curing.

The variations can be random or can be the result of changing environmental factors or work practices. Quality control is aimed at reducing these variations and thus the variation in strength. Non-systematic test errors introduce a further source of variation (systematic test errors should be largely eliminated by the quality control QC procedures). The specification of strength takes into account these variations by employing a statistical approach to strength determination, either explicitly (as in BS) or implicitly (as in ACI).

The strengths measured on specimens of apparently identical concrete show statistical variations that follow a normal distribution and this variation can be measured as the coefficient of variation (standard deviation / mean strength). The statistical approach is based on normal distribution (bell-curve) which is characterised by its mean and standard deviation. A large variation, expressed either as standard deviation or coefficient of variation, implies poor quality control. Fig. 5 shows schematic distributions for three different levels of quality control. The areas to the left of the specified strength ordinate and between the curves and the horizontal axis are the same in all cases. This area represents the allowable failure rate in the strength tests. The mean strength is the same as the target strength and this value increases with decreasing levels of quality control. The target strength is the strength used in design of the mixes. There are clear cost implications attached to quality control. Poor quality control will typically require the concrete to contain a higher proportion of cement. For large projects this can be significant in cost terms and will more than pay for the cost of tighter quality control. An increase in cement content may also be technically undesirable because of increased heat of hydration and attendant problems (i.e. cracking), see Chapter 6.

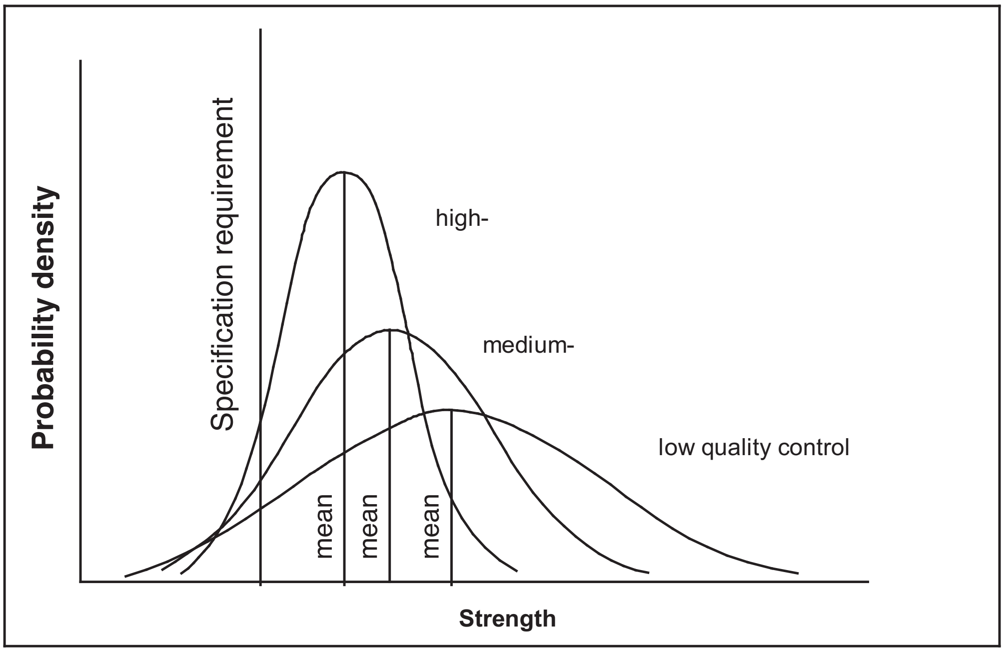

Fig. 5
Influence of quality control on required mean strength

The characteristic strength of the various concrete mixes at a given age will be given in the specification. A certain proportion of test results can be below the characteristic strength and this proportion is termed the failure rate. For each failure rate there is a factor derived from the properties of the normal distribution which when multiplied by the standard deviation gives the margin. As examples, this factor is 0.842 for a failure rate of 20%, 1.280 for a failure rate of 10% and 1.645 for a failure rate of 5%. The target strength is the sum of the characteristic strength and the margin. The target strength is the strength used as a basis for design of the mixtures. At the commencement of the concrete production the standard deviation will not be known. Coefficients of variation can be estimated on the basis of characteristics of concrete manufacture, transport, placing and other factors. Until such time as the strength test data from the concrete mixtures may be available and reliable coefficients of variation calculated, the coefficients of variation could be as much as 30% depending on the type of concrete mixer and transport system employed. ICOLD Bulletin N° 126, *The State of the art of Roller Compacted Concrete* gives details for setting initial coefficients of variation. As more test results become available the actual coefficients of variation can be estimated. In a well controlled operation the cementitious content will typically be reduced as a result of this process.

## 5.3. OTHER APPROACHES TO EVALUATING ACCEPTABLE VARIATION

The above means of evaluating strength is used explicitly in British and European standards and it underlies other codes and standards. ACI does not use this approach explicitly.

ACI 214 [17] is often applied to mass concrete and lists a standard for concrete control as shown on Table 4. ACI distinguishes between overall variation and within test variation, the latter being the sample-to-sample variation of specimens (generally three) of the same batch. It can be shown that for judging the quality of the material in the dam, it is the overall variation, measured as the standard deviation, which better defines variability, in contrast to the within-test variation, for which the coefficient of variation is a better measure. The fact that the standard deviation can be a quality parameter may be unexpected because it is strength-dependent. However, extensive evaluation from large construction sites with good quality control indicates that the standard deviation is independent of concrete with strength in excess of ≈ 20 MPa [5].

Table 4
Standards for Concrete Control (ACI 214)

| ***Overall variation*** | | | | | |
|---|---|---|---|---|---|
| Class of operation | Standard deviation for different standards of control (MPa) | | | | |
| | excellent | very good | good | fair | poor |
| Construction | 2.8 | 2.8 to 3.5 | 3.5 to 4.2 | 4.2 to 4.9 | > 4.9 |
| Laboratory | 1.4 | 1.4 to 1.8 | 1.8 to 2.1 | 2.1 to 2.5 | > 2.5 |
| ***Within-test variation*** | | | | | |
| Class of operation | Coefficient of variation for different standards of control (%) | | | | |
| | excellent | very good | good | fair | poor |
| Field control | < 3 | 3 to 4 | 4 to 5 | 5 to 6 | > 6 |
| Laboratory | < 2 | 2 to 3 | 3 to 4 | 4 to 5 | > 5 |

German guidelines are less demanding for overall variation with standard deviations of 3, 5, 7 and 9 MPa for excellent, very good, normal and poor control quality. This may be compared with a variation of about 6 MPa estimated for a 25 MPa concrete using a coefficient of variation of 30% and a 20% allowable failure rate.

The above ranges of standards are generally a too stringent judgement for dam concrete for which ranges of 10 to 12% are still considered as good to fair. On the other hand, it is known that variation in strength decreases with the age of concrete, this means that the above standards of control for, say, a 180-day or 365-day concrete come closer to what can be expected in concrete control for dams.

## 5.4. ESTABLISHMENT OF ACCEPTABLE FAILURE RATE

The Designer should establish criteria for strength requirements (percentages of tests falling below the specified strength). They should be based on the stress level in the dam, the level of knowledge about concrete constituents, the experience and reliability of the expected Contractor and the expected level of supervision during construction.

The setting of the failure rate percentage should also take into account the volume of the individual pours and their location in the structure. For mass concrete in gravity dams the allowable percentage of tests falling below the specified strength can be 20% (Ref. *USBR)*. This can be compared with a typical failure rate of 5% used for structural elements. In arch dams with higher stress levels the allowable percentages may be chosen between these numbers. The potential of redistributing stresses around local volumes of weak-strength concrete in arch dams is a valid remedy to avoid removal of weak concrete. The percentage for concrete in spillway chutes and other surfaces subject to high velocity water flow should be 5% as for structural concrete.

## 5.5. STRENGTH DEVELOPMENT OVER TIME

The increase in strength over time in relation to the commonly used 28-day strength is particularly marked in concrete containing pozzolan as well as cement. This makes pre-construction strength testing an important task for assessing concrete strength development in order to obtain the long term strength values, see Section 3.2. on trial mix programmes. Test results from low maturity concrete can serve as an indicator of strength at the specified maturity by using strength development curves obtained from the trials, usually months in advance. In some practices concrete cylinders and cubes have been subjected to accelerated cure (high temperature steam or water) and tested after 24 hours or other period up to 28 days. Such test results can be correlated with long term strengths obtained with normal curing procedures.

Criteria for changing the content of cementitious material require information about trends in strength development. Whenever there is a continuous production over a considerable period of time, as in dams, quality control charts have to be established. Most common is to plot moving averages of compressive strength, i.e. to plot the average of the previous 5 or 10 sets of test results. Comparing the development of the moving averages with the required strength gives a good indication for trends in strength development, see Fig. 6.

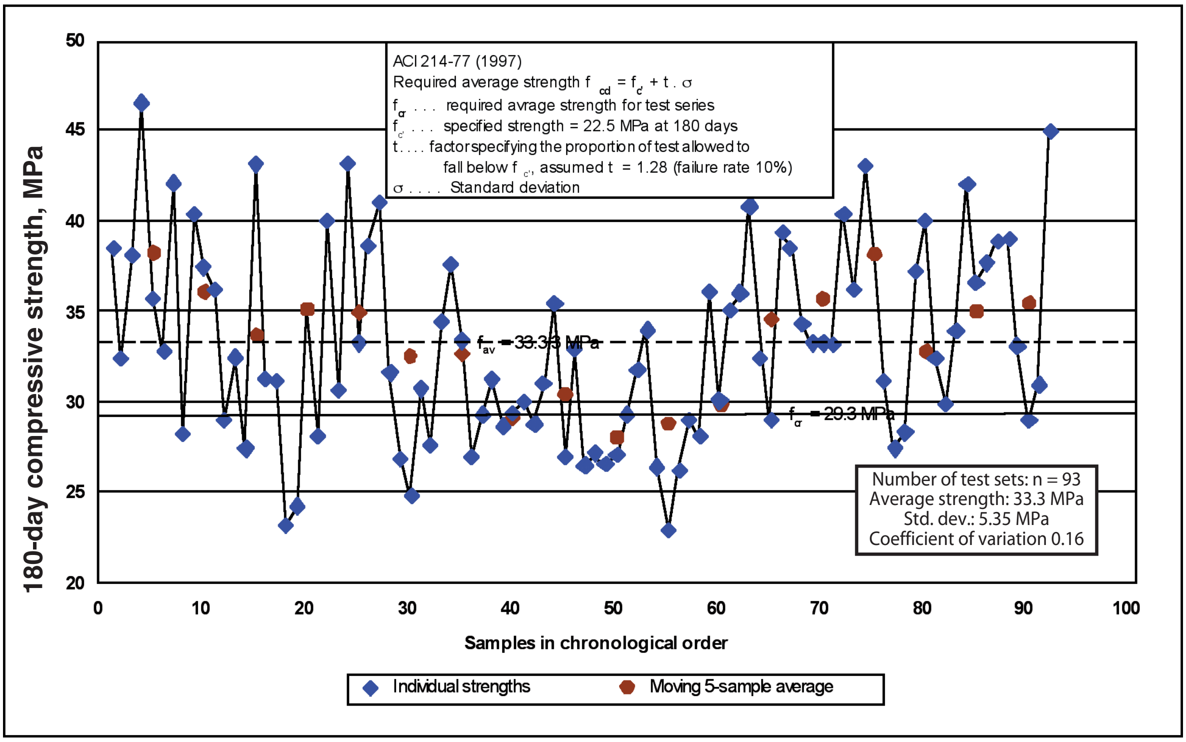

Fig. 6
Quality control chart for the interior concrete of an arch-gravity dam with rather poor standard of control

## 5.6. DEALING WITH UNDER STRENGTH CONCRETE

Removal of concrete which has not developed the design strength is normally very difficult and may be prohibitively expensive as it will typically be buried under other more newly placed concrete. This is particularly applicable in RCC dams with their high concrete placement rates. Although the concrete in conventional concrete dams will often be exposed for some days before it is covered by a new lift, and is thus accessible for demolition in this period, the cost of removal of a block of deficient concrete is still very high and such a process would disrupt the construction schedule. Should such an event occur in either type of concrete placement, the specification and quality programme for the project would have failed. The use of accelerated curing and testing of samples after 24 hours may permit removal of obviously defective concrete before it has been covered by subsequent lifts. (Defective concrete is mostly detected visually at the time of delivery and should already be suspect.) Such removal may be by using bulldozers (in the case of RCC) or high pressure water jets or sluicing (in the case of blocks of conventional concrete) if the process is started before substantial strength gain. Ultimately, hydraulic breakers and jack- hammers could be used on hard concrete given adequate access.

Acceptance of under strength concrete may have to be considered, but should only be undertaken after careful evaluation of a range of factors. Only if such an evaluation demonstrates that the function of the structure is significantly impaired should removal be contemplated. The sound engineering judgment required in the evaluation might take into account the following:

1. Stress re-distribution causes weak concrete to shed stress on to adjacent stronger concrete. This leads to the consideration of strengths averaged over large volumes of concrete. If these averages are judged to be satisfactory, the under strength concrete may be accepted. This concept is reflected in the typical allowable failure rate for strength tests for mass concrete of 20%.
2. The specified concrete strength is normally related to the maximum stress in the structure or zone of a structure. At all other locations the concrete will receive less stress and a lower strength may be acceptable.
3. In most cases the limiting strength is not compression but shear or tension and only in particular zones of the dam. Shear and tensile strengths are sometimes taken as percentages of compressive strength and are not measured in tests. These percentages are typical values derived from existing projects or extensive laboratory test series and are uncertain, particularly for dynamic loading. If shear and tensile strength values are estimated from percentages of compressive strength without site specific test series, as is common practice, the procedure may be justified if the strength governing structural stability is dominated by intact material strength. If, however, the structural strength is governed by the strength of joints or contacts, the simple procedure of using percentages may not be satisfactory. Testing of joint shear and tensile strength will then be required, initially in a test fill to establish the construction method, which will give the required strengths, and then on cores from the dam by means of verification.
4. Other defects, which may affect the performance of the structure, could include extensive honeycombing, but this is a matter for inspection and ensurance of good working practices rather than testing.
5. Durability will be related to strength. Durability is required to counteract long term degenerative forces such as wetting and drying, differential expansion and contraction due to temperature gradients and other causes. Durability is normally obtained by ensuring a minimum cementitious content and water/cementitious ratio and, in the case of frost durability, air entrainment. Durability is not related to strength as such.
6. Times when specified strengths are actually required. Long term strength gains will often result in concrete achieving the required specified strength.

Generally, as construction proceeds (and quality improves), the required mean strength, and with it the content of cementitious material, reduces. This will result in corresponding cost savings and reduced thermal effects. The possibility of such improvements should be reflected in the specification for the concrete, i.e. criteria for reducing the content of cementitious materials should be explicitly defined.

# 6. CONTROL OF CRACKING

## 6.1. INTRODUCTION

Control of cracking in concrete dams is discussed in detail in ICOLD Bulletin 107: *Concrete dams – Control and treatment of cracks* (1997). This Section is a short summary and update of that Bulletin and focuses on thermal cracking.

Mass concrete differs from structural concrete in that it is placed in thick sections where heat of hydration dissipates slowly and thermal shrinkage can induce cracking.

Detrimental cracks in mass concrete are caused primarily by tensile stresses developed in response to thermal shrinkage in combination with restraint to volume change. The restraint may be external, such as foundation rock, or internal such as that occurring between blocks of concrete of different maturity. Restraint can be reduced by providing contraction joints and temperature shrinkage can be controlled by reducing the peak temperature of the concrete and providing a concrete with low thermal shrinkage properties. The peak temperature is dependent on the placement temperature of the concrete, the heat of hydration and environmental heat loss and gain. The tensile strain capacity of the concrete, the strain at which cracking occurs, is also a factor. Tensile strain capacity is time dependent and the strength/stress relationship needs to be investigated at all ages and not only at the ultimate strength.

In addition to thermal cracking, which can have serious consequences for the performance of a structure, cracking through other causes can occur. These are drying shrinkage, which is normally not significant in mass concrete but may be so in the case of spillway slabs, and autogenous shrinkage. The latter is caused by the products of hydration occupying a smaller volume than the un-reacted constituents and is dealt with in the mix design. A further form of cracking is caused by plastic shrinkage where in dry environmental conditions the un-hardened concrete looses mixing water faster than it can be replaced by bleed water. Again, such cracking would not normally be a problem in mass concrete, but in spillway slabs plastic shrinkage cracks can penetrate the full section unless precautions are taken.

Cracking is of consequence where the crack size, spacing and orientation would affect the strength, water-tightness or appearance of the dam or the function of a spillway. The concrete has to be specified and controlled such that adverse cracking does not occur. Joints can be provided in gravity dams to reduce the block sizes to a point where thermal cracking will not occur given prescribed construction procedures. Arch dams in operation cannot have open cracks normal to their axis as they rely on load transfer along the axis for their stability. In this case cracks have to be grouted before impounding and the concrete has to be cooled to close to its long term mean value before grouting can start.

## 6.2. DESIGN OF CRACK CONTROL MEASURES

Control of cracking is largely a design issue. Various techniques are used to estimate stresses which may cause cracking. They can be complex finite element analyses where the time-dependent concrete properties are modelled along with predicted construction factors such as seasonally dependent concrete placement temperatures and environmental heat losses and gains, with curing processes taken into account. They can be two- or three- dimensional analyses made over many time steps up to a point where thermal equilibrium has been essentially achieved. Such analyses are commonly employed for RCC dams. The analyses are normally undertaken in two stages, firstly the prediction of the temperatures given particular placing temperatures and environmental conditions and secondly the prediction of the stresses within the dam arising from those temperatures for a given joint spacing. The joint spacing and placing temperature (and any post cooling measures) can then be adjusted until a satisfactory Factor of Safety is obtained. The location of openings through the dam such as orifice spillways and penstocks as well as abrupt changes in the longitudinal foundation profile, will typically dictate the location of some of the contraction joints as all these features cause stress concentrations in the concrete. Thermal stresses could crack the dam at these locations if these joints were not provided.

Caution is needed when basing decisions on temperature and stress estimates as stresses in massive dams cannot be determined with a high degree of accuracy due to indeterminate degrees of restraints (both internal and external) and varying concrete properties, particularly at low maturities.

Methods for preventing unwanted cracking in conventional concrete dams are well established; see for example ACI 207.4R-93 [13]. These dams are constructed in blocks which are allowed to cool, at least partially, before being covered by adjacent or overlying concrete.

If the combination of block size and concrete temperature drop are less than certain values, then simple measures can be used to prevent thermal cracking. These simple measures may be placement at a cool time of the day or year and moderate control of concrete placement temperatures. Gravity dams are commonly made from blocks divided by joints spaced at about 15 m and normal to the dam axis. They will extend from upstream to downstream unless this dimension (the block length) is very large. Table 5 indicates the allowable temperature drops at which temperature control and thermal cracking are not an issue. The changing temperature requirements with height above the foundation reflect the reducing effects of foundation restraint. Thermal cracks commonly start from the foundation where restraint to thermal movement is largest. Lift thickness near the foundation are limited, often to 1.5 m as against 2.5 or 3 m higher up in the dam.

Control by artificial cooling is frequently essential to avoid thermal cracking. The two applied techniques, pre- and post-cooling, have overlapping objectives.

- Pre-cooling reduces temperatures and thus temperature differences to ambient conditions. It can therefore be more important in cold than in hot regions. Pre-cooling is achieved by evaporative cooling of the aggregates in the stockpiles, by the spraying of the coarse aggregate on slow-moving conveyors with chilled water (wet belts), by submersion of coarse aggregates in chilled water, by air cooling of the coarse aggregate in the concrete plant bins and/or replacing part of the mixing water with chilled water and/or flake ice.
- Post cooling not only reduces peak temperatures but also allows control of temperature gradients, particularly at lift joints, the weak structural elements in a dam, where excess thermal stresses should be avoided by all means. In its

Table 5
Maximum allowable temperature drops as a function of block size and location
(based on table 7-4 in USBR, Design of Gravity Dams, 1976 and in EM34)

| **Block length** | **Treatment** | | |
|---|---|---|---|
| Over 60 m | Use longitudinal joints. Stagger longitudinal joints in adjoining blocks by minimum 9 m | | |
| | Temperature drop from maximum concrete temperature to operating temperature, 8C | | |
| | Foundation to H =0.2 L | H = 0.2 to 0.5 L | Over H = 0.5 L |
| 45 to 60 m | 14 | 19 | 22 |
| 36 to 45 | 17 | 22 | 25 |
| 27 to 36 m | 19 | 25 | No restriction |
| 18 to 27 m | 22 | No restriction | No restriction |
| Up to 18 m | 25 | No restriction | No restriction |

H = height above foundation, L = block length

simplest form post-cooling is cooling by radiation and evaporation of curing water. If this natural process is not sufficient to create a monolithic behaviour within the dam, cooling coils have to be placed. Cooling coils, comprising metal or plastic pipes installed in a pattern near the base of a concrete lift, can be used to substantially reduce heat gain from hydration of cement. Where cooling coils are used, lower lift thicknesses give opportunity for better temperature control.

Where grouting of joints is to be done, post-cooling can bring the mass concrete to near the specified temperature at the time of grouting, thus ensuring the water-tightness of the grouted joints as the combination of low concrete temperature at the time of grouting and the grout pressure will reduce the risk of the dam going into tension.

Mean concrete temperatures are a useful measure of degree of cooling when considering the time at which joint grouting should be done. The designers need to consider temperature gradients in order to avoid cracking. The rate of cooling should be set such that stresses resulting from the thermal gradients will not exceed the tensile strength of the concrete, noting that the tensile strengths are a function of concrete maturity.

Reinforcement is occasionally used in mass concrete to control surface cracking. Typical locations are overflow crest blocks and similar location exposed to high velocity water flows. To control thermal cracking the quantity of reinforcement steel would be excessive, in terms of constructability, cost and time schedule, and is not commonly used.

RCC dams are built in thin lifts from abutment to abutment. Transverse contraction joints are induced at designed locations and spacings. In very large dams there may be a longitudinal joint in its lower part where thermal stresses might cause uncontrolled cracking. The joints are commonly induced by inserting metal plates or plastic sheeting into the fresh concrete.

Estimates of concrete temperatures over time and the attendant stress calculations require good input data. Concrete properties are thermal and strength characteristics as a function of concrete maturity. Tensile thermal stresses are proportional to the coefficient of thermal expansion and this coefficient is dominated by the aggregate. This parameter has to be known with some precision. Environmental data comprise principally hourly rainfall, temperature, humidity and solar radiation. River water temperatures are also required and predictions of future reservoir temperatures are needed, as both may be required for, respectively, design of cooling measures and estimates of concrete temperature development. The concrete mix designs have to be prepared and physical tests made to determine concrete properties.

Tensile strength is related to the maximum size of aggregate (MSA) in the concrete and Designers have sought to increase the tensile strength by restricting the MSA and using crushed aggregate. However, restriction of the MSA is contrary to the requirement for the largest practicable MSA in order to reduce the cementitious content and heat of hydration.

In the design phase rules need to be established which will allow variation in cooling requirements in response to seasonal and short term temperature changes. Such factors are listed in Section 6.3.

## 6.3. SPECIFICATION

The specification will contain sections which deal with concrete constituents and proportions, constraints on concrete temperatures and workmanship. It should be written in such a way that the assumptions made in the design will be satisfied. Constructability, programme and cost issues have to be addressed and evaluation of these can lead to modification of the design requirements and assumptions. The writer of the specification should be aware of the costs of the various options available in order to keep costs as low as possible. The basis for a contract might be a performance requirement, but specification of methods may be developed with the Contractor when it is clear what methods the Contractor would implement.

Specifications can include items aimed at crack control. A list of items is shown in Appendix 3. These can include measures aimed at limiting the heat of hydration, limiting thermal movements, limitations on block sizes and spacing of contraction joints, limiting the maximum concrete temperature, requirements for internal cooling systems, curing and protection requirements and various construction procedures.

The drawings will show the location of construction and contraction joints, which define the block dimensions, and embedded cooling pipes.

## 6.4. PRINCIPAL QUALITY CONTROL ACTIVITIES

All concrete placement requires intensive quality control. The activity can be divided into pre-placement, placement and post-placement activities. Appendix 4 lists quality control items that may be included in the specification.

Where post-cooling with coils is used, a person who is experienced in the operation of such systems is required. There is a need for on-site computational competence to make the adjustments to the cooling procedures in response to the changing site conditions.

# 7. CONCRETE IN CONTACT WITH HIGH VELOCITY WATER FLOWS

## 7.1. SPECIFICATION OF PROPERTIES

### 7.1.1. Strength

The massive sections of spillway and control structures normally comprise mass concrete with a maximum size of aggregate of 75 mm to 150 mm and having moderate 28-day compressive strengths (typically less than 20 MPa). However, concrete which may be subject to abrasion and cavitation from high velocity flowing water or abrasion from sediments carried by flowing water is typically made from concrete with aggregate size limited to 40 mm and having a strength of 35 MPa or more and capable of receiving a smooth finish to a specified flatness. (Aeration of the water flow is used as a further means of minimising or eliminating cavitation damage.)

### 7.1.2. Properties of fresh concrete

The top surfaces of spillway overflows and chutes are typically unformed and are placed on slopes. In addition to abrasion and cavitation resistance conferred mainly by strength, the concrete must have properties when fresh which allow it to be placed, consolidated and finished to tight tolerances. Such concrete will typically have a high cementitious content and a moderate maximum aggregate size, well graded aggregate and modest slump. It requires internal frictional strength when wet to prevent it from flowing or sagging after consolidation on a slope or settling either side of large diameter surface reinforcement bars which will cause cracking along the axis of the bar. The concrete must contain sufficient mortar and paste to allow the production of a smooth finish. Like all other concrete, it is a compromise material where often conflicting properties have to be balanced.

### 7.1.3. Surface finish

On high velocity structures, clear water abrasion and cavitation are normally controlled by the smoothness and flatness of the finish of moderately high strength conventional concrete with the addition of aeration in many cases. In adverse conditions even the smallest of offsets in construction can initiate the cavitation process. Once started, large amounts of material can be eroded in a short period of time. Care has to be taken when making good and filling form anchor holes and the like to ensure that a smooth and durable finish is obtained.

### 7.1.4. Concrete for sediment-laden flows

Spillways that are required to pass sediments require abrasion resistant concrete. Such spillways are normally within dams on run-of river schemes and the heads and water velocities are modest, normally below velocities associated with cavitation damage. The concrete in such spillways may be required to resist the abrasion of suspended sand or the impact of gravel, cobbles and boulders in the bed load. The addition of fibres (steel and polymer) and silica fume has been used in attempts to improve the performance of concrete in such locations. Hard aggregate such as diabase, porphyry or basalt can also increase abrasion resistance. Other solutions have departed from the use of concrete and materials such as hard natural stone blocks (granite or similar) have been used instead. Steel armour is used at locations that will be subject to heavy abrasion or cavitation, such as immediately downstream of high velocity gates.

Many spillway structures, including the energy dissipaters, have received abrasion and cavitation damage and many are routinely repaired. Repair of concrete on hydraulic surfaces is a specialist topic outside the scope of this bulletin.

No material can withstand cavitation damage over time. Harder materials will perform better. Elimination, or at least reduction, of conditions that cause cavitation are a design issue as important as providing resistant concrete. Good finish and good detailing of joints are of great importance.

## 7.2. SPECIFICATION

Concrete with high abrasion and cavitation resistance typically has a moderate maximum size of aggregate (e.g. 40 mm), high cementitious content, low water-cementitious ratio, carefully graded aggregate and will contain water reducing additives and air entrainment agents. Silica fume has been used to produce very high strength concrete. Hardness and dense packing of the aggregate enhance resistance to damage in normal strength concrete, as the cement paste is the weakest part of the concrete. The design may have to consider the balance in strength between aggregate and mortar, particularly when weak aggregate is used. In very high strength concrete, the aggregate properties are of less importance as the paste is more resistant to damage.

The concrete should be at the lowest possible slump that can be effectively consolidated.

The finish of the concrete is commonly specified as a flatness criterion, such as allowable deviation from a straight line of given length or as limits on off-sets and angles of ramps on the concrete surface, or a combination of these. Further specification of the finish requires a hard, dense and smooth surface made by steel trowelling. Methods for ensuring a good and crack-free finish are commonly given in the specification.

The treatment at longitudinal and transverse joints is normally specified. Transverse joints are normally kept to a minimum with reinforcing steel limiting crack size in the intervening concrete.

The concrete should have a composition which will allow screeding and trowelling to be done easily with minimum rework of the concrete surface. Over-working the concrete can bring excessive fines to the surface. The surface may then be less durable than required.

Conveyors and buckets are commonly used for delivery to the point of placement. Typically the mixture will not be pumpable and this method of transport should in general be disallowed. However, there are examples of pumped concrete being used successfully for spillways where good equipment, experience and extensive testing have been necessary factors.

The specification may include requirements for the placing equipment. Mechanical screeds mounted on rails may be used. These screeds receive the concrete, distribute it over the placement width, level it and give the initial finish with rotating steel drums. Winches are provided to move the screed up the slope. Final finishing by hand or rotating trowels can be done from a finishing bridge following the screed. In hot climates shading of the concrete surface may be required to prevent solar heat gain between the time of placement and final finishing. This period may be some hours. Night placement may be required to reduce heat gain and provide lower concrete temperature at placement.

Appropriate methods and times of curing have to be specified. In addition to keeping the surface of the concrete moist, prevention of solar heat gain through the use of shading may be required in hot climates. Curing may be particularly critical for some concretes including those containing silica fume.

Before concrete is placed on the spillway chute, it is good practice to make a trial placement on a section of prepared slope of the same angle as the steepest section of the spillway. All the features that will be encountered on the spillway should be incorporated in the trial. The trial serves to test the mix design, placing and finishing methods and as a training ground for the operators and supervisors. The concrete or finishing specification may be amended following the trials in order to more easily achieve the required properties of the hardened concrete and its surface.

## 7.3. QUALITY CONTROL

The quality control process of the concrete for high-velocity structures is the same as for any other concrete, but is normally more stringent. The appearance of the concrete at delivery is, as always, important. The appearance as it is worked and finished has to be followed. The method of screeding and finishing the surface require careful inspection. Free water should not appear on the surface if the mix proportions are correct. Exceptionally, such water can be removed by sponging. There is a constant temptation to overcome problems in finishing by adding water or paste, sprinkling with dry cement and other undesirable practices which can all lead to a surface that is less durable than required. Constant vigilance on the part of the quality control inspectors is required. Such problems are much less common when the concrete is correctly proportioned to allow easy finishing.

The flatness of the concrete surface is commonly checked with straightedges of specified lengths and its smoothness by inspection only.

# 8. CASE HISTORIES

## 8.1. SARDAR SAROVAR DAM

### 8.1.1. Introduction

The Sardar Sarovar (Narmada) Project is a multipurpose project on the west-flowing Narmada River in Gujarat State, India. The length of the reservoir is 214 km with a capacity of 9.50 × 109 m$^3$ of water of which 5.86 × 109 m$^3$ of water will be useable during normal operation.

The main concrete gravity dam has a length of 1 210 m and a mild curvature radius of 7 600 m with a maximum height of 163 m. The total volume of concrete is 6.82 million m$^3$. Fig. 7 shows the dam under construction.

The dam body has thirty radial gates of which 23 gates are located on the dam and 7 are in the chute spillway. The total discharge capacity is 87 000 m$^3$/s and is the third largest in the world.

There are two power houses. One is the 1 200 MW Underground River Bed Power House with 6 Francis reversible turbine generators and the other is the 250 MW Canal Head Power House with 5 Kaplan units.

Fig. 7
Sardar Sarovar dam under construction

### 8.1.2. Evaluation of aggregates

Shoals in the Narmada River Channel at a distance of 24 to 29 km d/s from the dam site were identified and approved as source of raw materials. The investigations for quarries were made in the 1960's and final selection was done based on quality and quantity of available aggregates. Quantities and gradation data of sand and coarse aggregates obtained from these shoals are given hereunder in Table 6.

Table 6
Aggregate sources and natural gradings

| **Particulars** | **Tilakwada** | **Nani Vandaria** | **Vandaria** |
|---|---|---|---|
| Approximate distance (km) | 24 | 26 | 29 |
| Approximate quantity (Mm$^3$) | 5.5 | 1.8 | 1.5 |
| Gravel/Sand ratio | 72/28 | 70/30 | 62/38 |
| Coarse Aggregate Gradation %<br>200 mm | 1.5 | 0.2 | — |
| 150 mm | 2.4 | 1.8 | 0.6 |
| 75 mm | 28.1 | 27.2 | 12.2 |
| 38 mm | 29.1 | 23.5 | 28.5 |
| 20 mm | 19.4 | 23.0 | 30.2 |
| 10 mm | 11.4 | 10.1 | 14.2 |
| 5 mm | 8.1 | 14.2 | 14.3 |
| Fineness Modulus of sand | 2.6 | 3.3 | 2.8 |
| Percentage of silt content in sand | 3.5 | 2.6 | 2.9 |

The table indicates that the sources contain materials of suitable gradation meeting the requirements of specifications as laid down in BIS: 383-1970 for sand and coarse aggregates. All the tests required to conform to BIS: 2386 (Part-I to VIII) (see Table 8) for mechanical properties. The silt content of the aggregate was reduced to less than 3 % during processing. All tests, except for alkali-aggregate reactivity, were carried out in the project laboratory.

### 8.1.3. Cement and pozzolan

Three major cement plants, Narmada Cements, Gujarat Ambuja Cements and Gujarat Sidhee Cements, were identified and approved prior to construction. The Portland Pozzolana Cement (PPC) conforming to BIS: 1489 (Part-I)-1991 was used for mass concreting work of the dam. The cement was transported to site in bulk carriers. Sampling and testing of cement samples was carried out to BIS and specification requirements.

Parallel testing of cement samples was carried out at several laboratories to ascertain the reliability of the test results. The test results were found to be satisfactory.

Fly-ash was transported by the cement manufacturers from a nearby thermal power station for use as pozzolan to produce the PPC. The required percentage of pozzolan was mixed with clinker during the grinding process. Physical as well as chemical analysis of fly-ash was carried out to BIS: 1727-1967 and BIS: 3812-1981 respectively to ensure its suitability for use in producing PPC. The quality of the fly-ash was monitored by regular testing, particularly lime reactivity and chemical composition, at the manufacturing plant and project laboratories.

### 8.1.4. Concrete Properties

Almost eighty percent of the chilled concrete poured in Sardar Sarovar Dam (SSD) is mass concrete i.e. $A_{150}$ $S_{160}$ grade (the suffix to A gives the maximum size of aggregate, the suffix to S gives the 28-day strength in kg/cm$^2$). Several concrete mix designs for different locations of the dam have also been carried out as shown in Table 7.

Concrete samples were collected from the batching and mixing plant and test specimens were 150 mm dia. × 300 mm for compressive strength measurement. For casting specimens with 75 mm or 150 mm MSA., wet screening to remove particles larger than 40 mm was done. For every 50 000 m$^3$ of mass concrete placed in the dam, cylindrical test specimens of 600 mm × 1 200 mm were made without wet screening. These were tested in a 2 000 tonne compression testing machine.

### 8.1.5. Concrete Production and placement

Two concrete manufacturing plants were installed, one on each bank of the river. The left and right bank plants had capacities of 5 000 m$^3$/d and 3 000 m$^3$/d respectively. Each installation consisted of a comprehensive aggregate screening plant and batching and mixing plant including chilled water plants and ice-makers. The batching of the concrete was computer controlled. The left bank installation had four 4.5 m$^3$ drum mixers with a combined output of 330 m$^3$/h. The right bank installation had two batch plants with a combined output of 240 m$^3$/h.

A cable crane was used to deliver the concrete to the placements in the dam.

From temperature considerations, all concrete to be placed in the dam, except those components where pre-cooled concrete is not envisaged, was to be pre-cooled with a placing temperature not more than 130 °C. The temperature was measured after concrete was placed and compacted in the forms. Concrete was not permitted to be placed at temperature above 15.5 °C and then only in exceptional circumstances.

Pneumatic vibrators having a capacity of 150 m$^3$ per hour mounted on a backhoe were being used for the compaction of concrete. The vibrator had a diameter of 150 mm and a length of 1.1 m. For one cubic meter of concrete, the time requirement for the compaction was 25 to 30 seconds.

Air entrainment was used to enhance wet and hardened concrete properties. The agent was a liquid solution prepared in the project laboratory. In a 200 litre drum, 15.48 kg of rosin and 1.62 kg flaked caustic soda were added to 180 litre warm water. The dosage of air entraining agent (AEA) was 150 ml per cubic meter of concrete. The cost of AEA was Rs.0.70 (US$ 0.015) per cubic meter of concrete.

### 8.1.6. Quality Control System during dam construction

The Quality Control system comprises the following main activities:

- (i) Control of production process by inspection of the equipment, particularly the concrete plants and the aggregates processing plants.
- (ii) Control by testing and inspection of the properties of the concrete constituents.
- (iii) Control of concrete batching by inspection of load cells, deviation records, water content of fine aggregates and W/C ratio.
- (iv) Control of fresh concrete sampling and testing.
- (v) Control of hardened concrete by testing samples and statistical conformity analysis.

The contract documents included specifications for aggregates, cement, water (ice), admixtures for concrete batching. Slump and air content were also specified for the different mixes. The mix designs were developed by number of trial mixes in the project laboratory by the Quality Control Organisation. The mix design and trial mix programme anticipated varying the cement content in response to changing coarse aggregate gradings and fineness modulus of the sand. In actual working almost negligible changes were made as the properties of the concrete constituents remained close to those used in the mix design. Table 7 below shows concrete classification and cement factors for use in different locations.

The quality control organisation is shown in Fig. 8. In the figure, “Inspection and Products Control” shown under the contractor’s organisation relates to workmanship as well as plant, machinery and construction equipment. All the

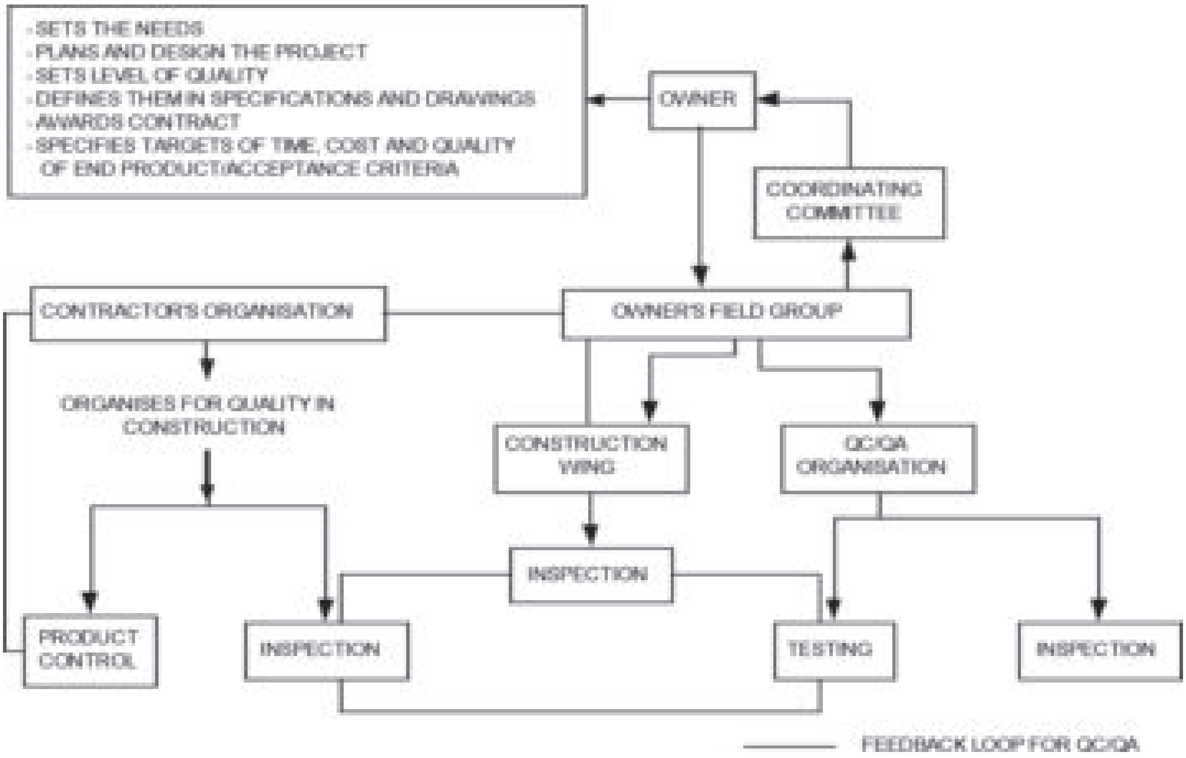

Fig. 8
System for quality control in construction

## Table 7
Concrete classification and cement factors for use in different locations

| No. | Item | Mix | Cement kg/m$^3$ |
|---|---|---|---|
| (i) | Non overflow dam, power dam and transition blocks | | |
| (a) | Main Body | | |
| | 1. Bottom layer | $A_{75}\ S_{160}$ | 200 |
| | 2. Other lifts | $A_{150}\ S_{160}$ | 160 |
| (b) | Around galleries | | |
| | Penstocks, adits, shafts, All block outs, 1st and 2nd stage concrete and other openings | $A_{40}\ S_{210}$ | 270 |
| (ii) | Spillway blocks | | |
| (a) | Main Body | | |
| | 1. Bottom layer | $A_{75}\ S_{160}$ | 200 |
| | 2. Other lifts of hearting | $A_{150}\ S_{160}$ | 160 |
| (b) | Around galleries, Shafts and Openings | $A_{40}\ S_{210}$ | 270 |
| (c) | U/S reinforced face | $A_{40}\ S_{210}$ | 270 |
| (d) | Crest, glacis and sluices | $A_{40}\ S_{350}$ | 450 |
| (iii) | Construction sluices plugging and block-outs | | |
| | (non-shrink type(a)) | $A_{150}\ S_{160}$ | 160 |
| | (non-shrink type(b)) | $A_{40}\ S_{210}$ | 270 |
| (iv) | Sloping apron and chute floor | | |
| | (a) Bottom layer | $A_{150}\ S_{160}$ | 160 |
| | (b) External 1m thick layer (Crushed coarse aggregate) | $A_{40}\ S_{350}$ | 450 |
| (v) | Divide walls, Training walls | $A_{75}\ S_{260}$ | 260 |
| (vi) | Spillway bridge | | |
| | a) Piers | $A_{75}\ S_{260}$ | 260 |
| | b) Beams (Crushed coarse aggregate) | $A_{40}\ S_{210}$ | 320 |
| | c) Slab (Crushed coarse aggregate) | $A_{20}\ S_{210}$ | 320 |
| | d) Wearing coat, parapet and kerb (Crushed coarse aggregate) | $A_{20}\ S_{210}$ | 320 |
| (vii) | Trash-rack intake structure | $A_{40}\ S_{210}$ | 270 |
| (viii) | No fines concrete | $A_{20}\ S_{210}$ | 400 |

Note : (i) ‘A’ denotes aggregates and suffix to ‘A’ the maximum size of aggregate in mm
(ii) ‘S’ denotes strength and suffix to ‘S’ the specified design strength of concrete at 28 days in kg/cm$^2$ on 150 mm dia × 300 mm cylinder.

testing work was carried out by the project authorities. The testing should was in effect also a service to the contractor to enable him to fulfil his obligations to quality. Such linkage is shown by dotted lines in the figure.

Fig. 9 shows the Quality Control Organisation set up for construction. The test results and subsequent analysis were forwarded to the Superintending Engineers for any necessary corrective measures, supported by the Design Team.

In the Quality Control Plan, all responsibilities of the staff were clearly set out and the Quality Control System followed these guidelines.

The scope of the inspection and testing activities is shown in Fig. 10. This diagram represents the main quality system applied on this project. All actions have written procedures which establish who, how, when and what must be done. Each procedure and testing plan has its own records in order to trace of all non-conformities and each non-conformity was communicated to the Execution wing.

Scope of inspection of testing activities

### 8.1.7. Concrete Mix design

The different grades of concrete mixes used are as shown in Table 7 above.

The construction specifications required testing of samples of aggregates, cement and concrete. Based on the project reports on investigations for coarse and fine aggregates, the design mixes were developed. From this testing, the detailed specifications for the tender were prepared so as to minimise or avoid variations in the design mix. At the work site coarse and fine aggregates were tested for their grading and moisture content before preparing the concrete mixes. Concrete cylinders were cast in each shift for compressive strength testing and analysis.

Mixing time for concrete was computerised so as to maintain consistency of concrete. Temperature of the concrete mix was also measured at the mixing plant and placement site. Cores were taken from hardened concrete at the end of each working season for testing compressive strength, at the rate of one test for 50 000 $m^3$ of concrete. The design of any concrete mix not stipulated in the contract, is also prepared and tested by the Q. C. Wing. Such mixes were adopted first on trial basis in field and if found suitable, incorporated as regular mixes.

### 8.1.8. Documentation

All the documents related to Quality Control works such as logbooks of concrete placements, shift reports, Quality Control reports, technical specifications etc. were controlled documents and were preserved for storage, retrieval and safe custody.

To ensure compliance with the specifications and construction drawings, a system of check lists was developed and adopted at the work site. This is an important document containing approvals of day to day construction activities. Every inspection and test was recorded and all the test results were regularly entered in the computer for statistical analysis. A comprehensive Quality Control report was prepared for each construction season listing all test results, their statistical analysis with any recommendations.

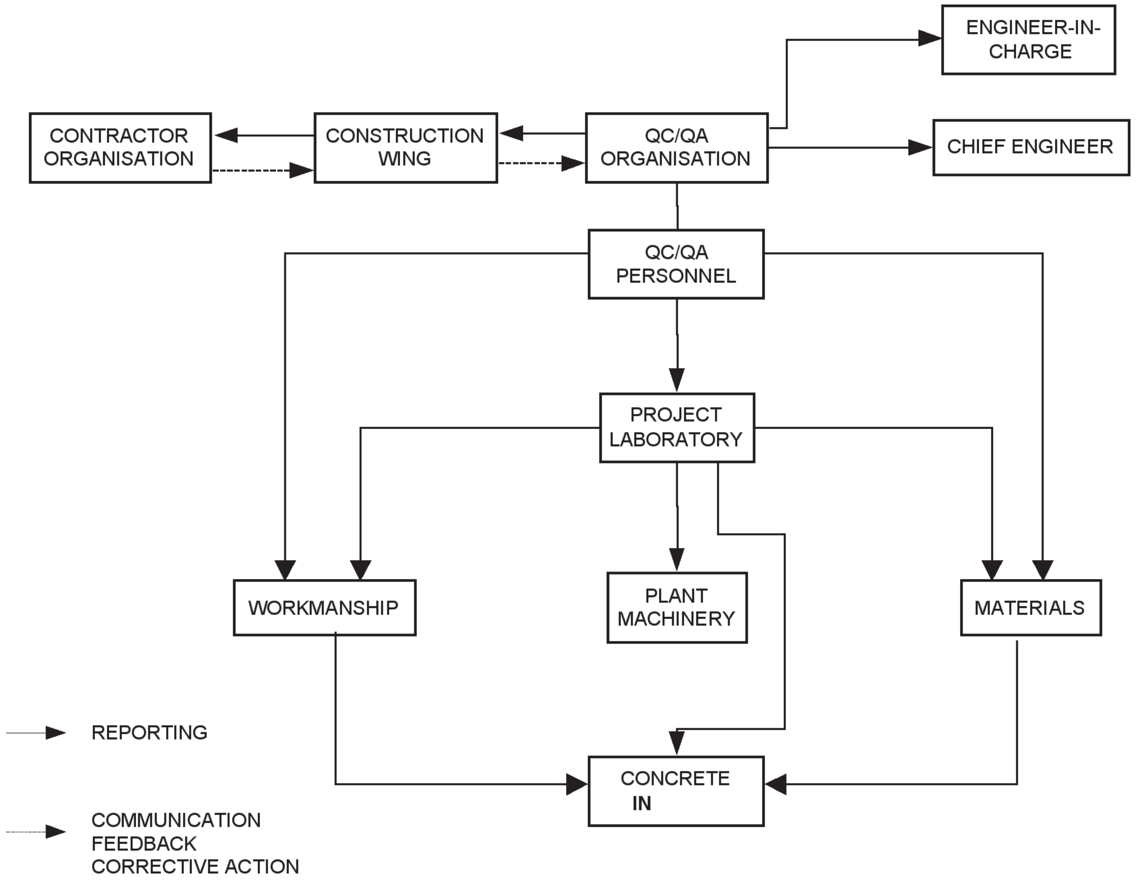

Fig. 9
QC/QA organisation

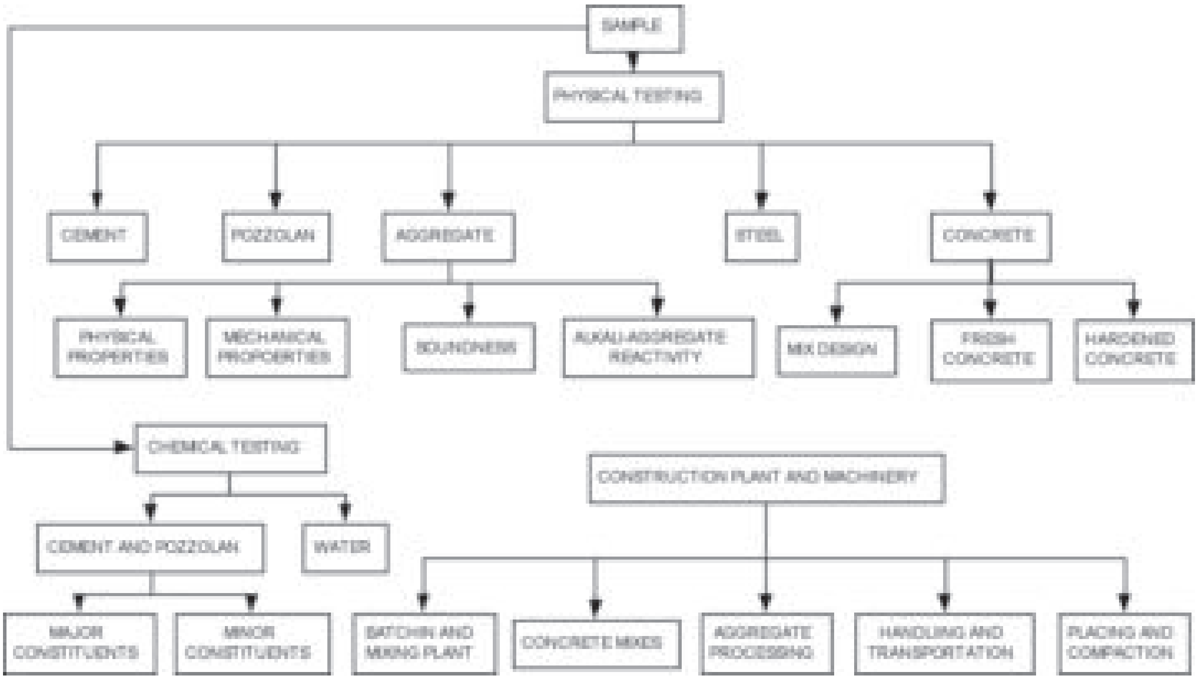

Fig. 10
Scope of inspection of testing activities

### 8.1.9. Process Control

The process control was applied mainly to concrete production, transportation of concrete, placement, curing etc. The batching and mixing plant records for each batch produced including batch number, mix designation, location of concrete placement and date and hour of mixing. Quality Control staff monitored the variation of each constituent and corrections were applied as required. Hourly consumption of each constituent in the various concrete mixes was recorded as well as any corrective actions. Each sample obtained for Quality Control testing and the test results were registered by the Quality Control staff. The load cells of weigh batchers were regularly calibrated. Before concreting started, all items were checked and recorded on the checklist. During concreting, execution staff recorded temperature of concrete placed, time of concreting and any interruptions during concreting etc.

### 8.1.10. Tests and Inspection

Visual inspection was made routinely of aggregate screening plant, immersion bins, cement silos (filters and water-tightness) and calibration of batch plant load cells. Testing and of concrete constituents and concrete was made as shown in Table 8.

### 8.1.11. Non Conformity Control and Statistical Techniques

After testing and inspection, if non-conformity was observed, the Q.C. staff conveyed the same to the execution wing for corrective action. Occasionally the Design Wing was involved in discussions.

### 8.1.12. Test Equipment Control

The Quality Control Plan had a complete list of laboratory equipments at project laboratory with requirements for all appropriate calibrations and routine checks.

### 8.1.13. Statistical Analysis of field compressive strength of concrete

A typical statistical analysis of field 28-day compressive strength of test results of $A_{150}$ $S_{160}$ concrete for a one-year period for the main dam concrete is shown in Fig. 11. The 5-test moving average strength is also shown. The analysis indicated that overall objective of QC / QA was achieved. Such quality control reports were prepared for each year.

### 8.1.14. References

Bureau of Indian Standards

| | | |
|---|---|---|
| BIS 4031 | 1996 | Parts 1 to 15. Methods of physical tests for hydraulic cement |
| BIS 516 | 1959 | Method of test for strength of concrete |

Table 8
Tests performed on concrete and its constituents

| **Material** | | **Test** | **Method** |
|---|---|---|---|
| Cement | a) | Chemical | BIS:4032-1985 |
| | i) | $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO, $SO_3$, Insoluble residue & Loss on Ignition | |
| | ii) | Alkalis & Chlorides | |
| | iii) | Free Lime | |
| | b) | **Physical** | |
| | i) | Specific gravity | BIS:4031-1988 |
| | ii) | Fineness | |
| | iii) | Setting time | |
| | iv) | Soundness | |
| | v) | Compressive strength | |
| | vi) | Drying Shrinkage | |
| | vii) | Heat of hydration | |
| **Pozzolan** | a) | **Chemical** | BIS:3812-1981 |
| **(Fly-ash)** | i) | $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO, $SO_3$ & Loss on Ignition | |
| | b) | Physical | |
| | i) | Fineness | BIS:1727-1967 |
| | ii) | Lime reactivity | |
| **Aggregates** | a) | **Physical** | BIS:2386-1963 |
| | i) | Sieve analysis | Part-I |
| | ii) | Flakiness Index | Part-II |
| | iii) | Elongation Index | |
| | iv) | Deleterious materials | |
| | b) | **Mechanical Tests** | |
| | ix) | Aggregate crushing value | Part-IV |
| | x) | Impact value | |
| | xi) | Abrasion value | Part-V |
| | xii) | Soundness | Part-VII |
| | xiii) | Potential reactivity of aggregate | Part-VIII |
| | xiv) | Petrographic examination | |
| **Water** | | **Chemical** | |
| | i) | Chlorides, Sulphates, Organic & Inorganic solids, PH, Alkalinity/Acidity | BIS:3025-1964 |
| | ii) | Setting time of mortar | BIS:516-1959 |
| | iii) | Relative strength of concrete | BIS:1199-1959 |
| **Admixtures** | i) | Relative Water Content | BIS:9103-1979 |
| | ii) | Relative strength | |
| **Fresh Concrete** | i) | Slump | BIS:516-1959 |
| | ii) | Unit Weight | |
| | iii) | Yield | |
| | iv) | Air entrainment | |
| | v) | Temperature | |
| **Hardened Concrete** | i) | Compressive strength | |
| | ii) | Core Testing | BIS:516-1959 |

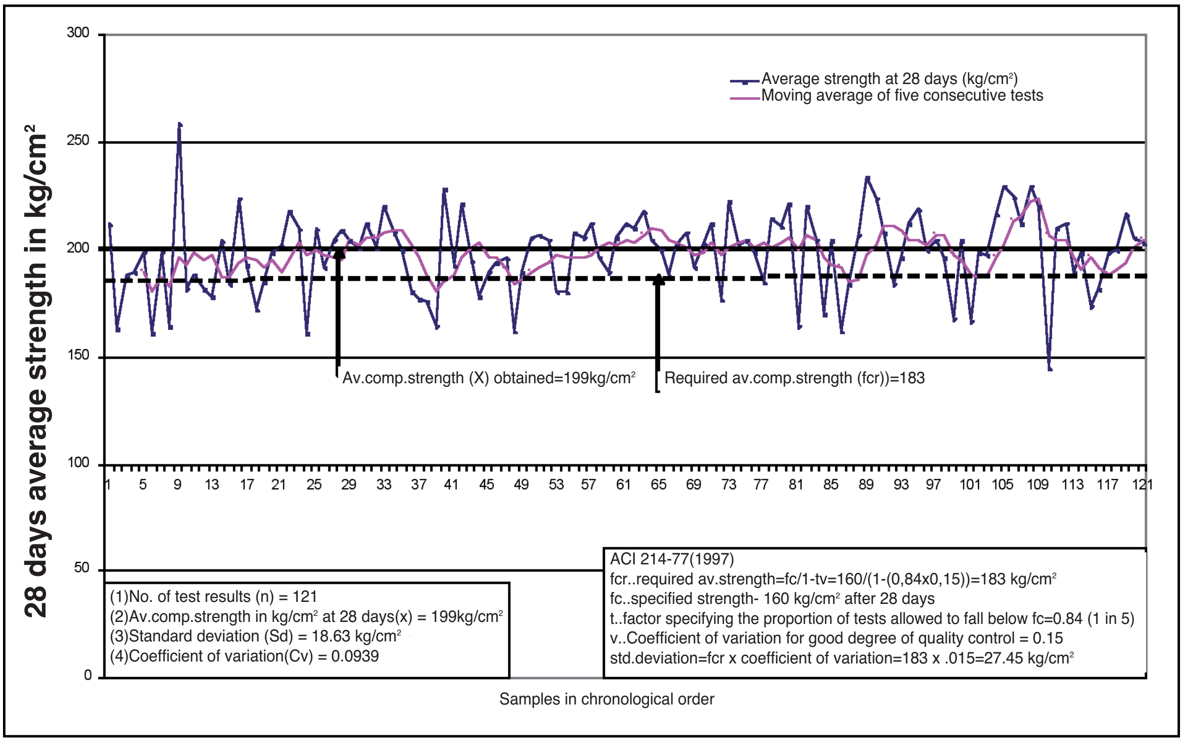

Fig. 11

Quality Control Chart of $A_{150}$ $S_{160}$ concrete from July 2000 to June 2001

| | | |
|---|---|---|
| BIS 1199 | 1959 | Methods of sampling and analysis of concrete |
| BIS 9103 | 1999 | Specification for admixtures for concrete (First Revision) |
| BIS 1727 | 1967 | Method of test for pozzolanic materials |
| BIS 383 | 1970 | Specification for coarse and fine aggregates from natural sources for concrete |
| BIS 2386 | 1963 | Parts – 1 to 8 Methods of test for aggregates for concrete |
| BIS 3812 | 1981 | Specification for flyash for use as pozzolan and admixture (First Revision) |
| BIS 1489 | 1991 | Part 1 and 2. Specification for Portland pozzolan cement |
| BIS 3812 | 2003 | Part 1 and 2. Pulverized fuel ash specification |

## 8.2. OLIVENHAIN ROLLER COMPACTED CONCRETE DAM

### 8.2.1. Introduction

The Olivenhain Dam is a roller-compacted concrete (RCC) gravity dam located near San Diego, California and was completed in August 2003. A photograph of the dam at approximately 97% completion is shown in Fig. 12. The dam is the tallest RCC dam constructed in the United States and the first RCC dam in the state of California. Main features of the dam are summarized in Table 9.

Fig. 12
Olivenhain Dam at Approximately 97% Completion

Table 9
Summary of Olivenhain Dam Features

| | |
|---|---|
| Maximum Dam Height | 104 m (318 ft) |
| Maximum Dam Length | 788 m (2 586 ft) |
| Reservoir Capacity | $3.4 \times 10^6$ $m^3$ (24 800 acre-feet) |
| Volume of RCC | $1.07 \times 10^6$ $m^3$ ($1.4 \times 10^6$ $yd^3$) |

### 8.2.2. Specification of concrete

During the design stage, a RCC mix design was developed as shown in Table 10. The dam design required a 20 MPa (3000 psi) concrete strength for the main dam at 365 days and a 17 MPa (2500 psi) strength for the foundation replacement “shaping blocks”. After the award of construction contract, the contractor offered a value-engineering proposal that modified the original mix to eliminate the mandatory bedding mix between each lift by making the parent material richer in paste. The proportions of the value-engineering RCC mix are shown in Table 11. A comparison between the original and value-engineering mixes is summarized in Table 12. The Contractor proposed this change to increase production by the elimination of the bedding mix work. A summary of RCC production is shown in Table 13.

Table 10

Original RCC Mix Proportion

| Location | kg/m$^3$ (Pounds per Cubic Yard) | | | Percent by Weight | | |
|---|---|---|---|---|---|---|
| | **Cement** | **Fly Ash** | **Max Water** | **1.5” × ¾”** | **¾” × #4** | **#4 minus** |
| Main Dam | 89.1<br>(150) | 74.2<br>(125) | 109.9<br>(185) | 28 | 24 | 48 |
| Shaping Blocks | 59.4<br>(100) | 59.4<br>(100) | 109.9<br>(185) | | | |

Table 11

Value Engineering (VE) RCC Mix Proportion

| Location | kg/m$^3$ (Pounds per Cubic Yard) | | | Percent by Weight | | |
|---|---|---|---|---|---|---|
| | **Cement** | **Fly Ash** | **Max Water** | **1.5” × ¾”** | **¾” × #4** | **#4 minus** |
| Main Dam | 74.2<br>(125) | 121.1<br>(204) | 132.4<br>(223) | 32 | 29 | 39 |
| Shaping Blocks | 59.4<br>(100) | 133.6<br>(225) | 128.9<br>(217) | | | |

Table 12

Comparison of RCC Mix Properties

| | Original RCC Mix | Value Engineering RCC Mix |
|---|---|---|
| Bedding mix between lift? | yes | no |
| Weakest materials in tension | Parent materials | Lift joint |
| Percentage of fine aggregates | 48% | 39% |
| VeBe time | 17 to 27 seconds | 15 to 17 seconds |
| Water content | 109.9 kg/m$^3$<br>(185 lb/cu yd) | 121.1 kg/m$^3$<br>(204 lb/ cu yd) |
| Compressive Strength @ 365 days | 20 MPa (3000 psi) | 26.9 MPa (3900 psi) |
| Tensile Strength of the weakest materials @ 365 days | 1.4 MPa (200 psi) | 1.5 MPa (220 psi) |

### 8.2.3. Project delivery system

There are six main parties that work together with a common goal, i.e. to build a safe, reliable, durable, and cost-effective emergency storage water reservoir, the Olivenhain Dam Project. These parties are the owners, San Diego County Water

Table 13
Summary of RCC Production

| Item | Production Rate, m³ (yd³) | Total Volume, m³ (yd³) | Last Recorded Data, m³ (yd³) | Ratio of (3) to (4) |
|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) |
| Monthly Average | | 127 418<br>(166 656) | 132 727<br>(173 600) | 96% |
| Daily Maximum | 614 (802.8)<br>× 20 hrs | 12 276<br>(16 056) | 12 218<br>(15 980) | 100.5% |
| Monthly Max. | 9 006 (11 779)<br>× 25 days | 225 134<br>(294 464) | 204 366<br>(267 300) | 110.2% |

Authority (the Authority) and Olivenhain Municipal Water District (the District), the regulatory agency, California Department of Water Resources - Division of Safety of Dams (DSOD), the Board of Senior Consultants (BOSC), the Construction Management team, the Design Engineer and the Contractor.

The RCC Designer assisted the Design Engineering team in developing the original RCC mix design. During the development of the value-engineering mix, the Contractor was assisted by Specialist RCC Consultant. The interaction among these parties is shown in Fig. 13.

### 8.2.4. Quality control system

The Quality Control (QC) system is depicted in Fig. 14. There are two basic elements of the QC program: testing and inspection. The Contractor has a similar but smaller QC system. Generally, the Contractor is responsible to make sure the product meets the specification and drawings. The construction management (CM) organization conducts the "Record" testing and inspection that is used for final acceptance and the project record. A table showing the tests performed and the responsibility distribution is shown in Table 14.

Accuracy and timeliness of test results are the primary goals of testing. These elements are maintained by regular calibration of the test equipment, development of efficient test procedures according to standard procedures, calculations, and a computer database. The regular calibration of test equipment ensures the functional and accuracy of the equipment. Any equipment found working improperly is clearly marked out of service so that no technician may uses it for testing. The development of test procedures ensures that the materials are prepared efficiently for different tests and tested properly in accordance with the standard test procedures, specifications, and industry standards. The Laboratory Manager carefully watches the implementation of the test procedures and reviews the test data before entering the data in the computer database. The computer database recalculates the test calculation for a second check, stores the test data, and generates the test reports.

Inspection is divided into plant and placement inspections. Quarry, rock crushing, and concrete and RCC batch plants are the elements of plant inspection.

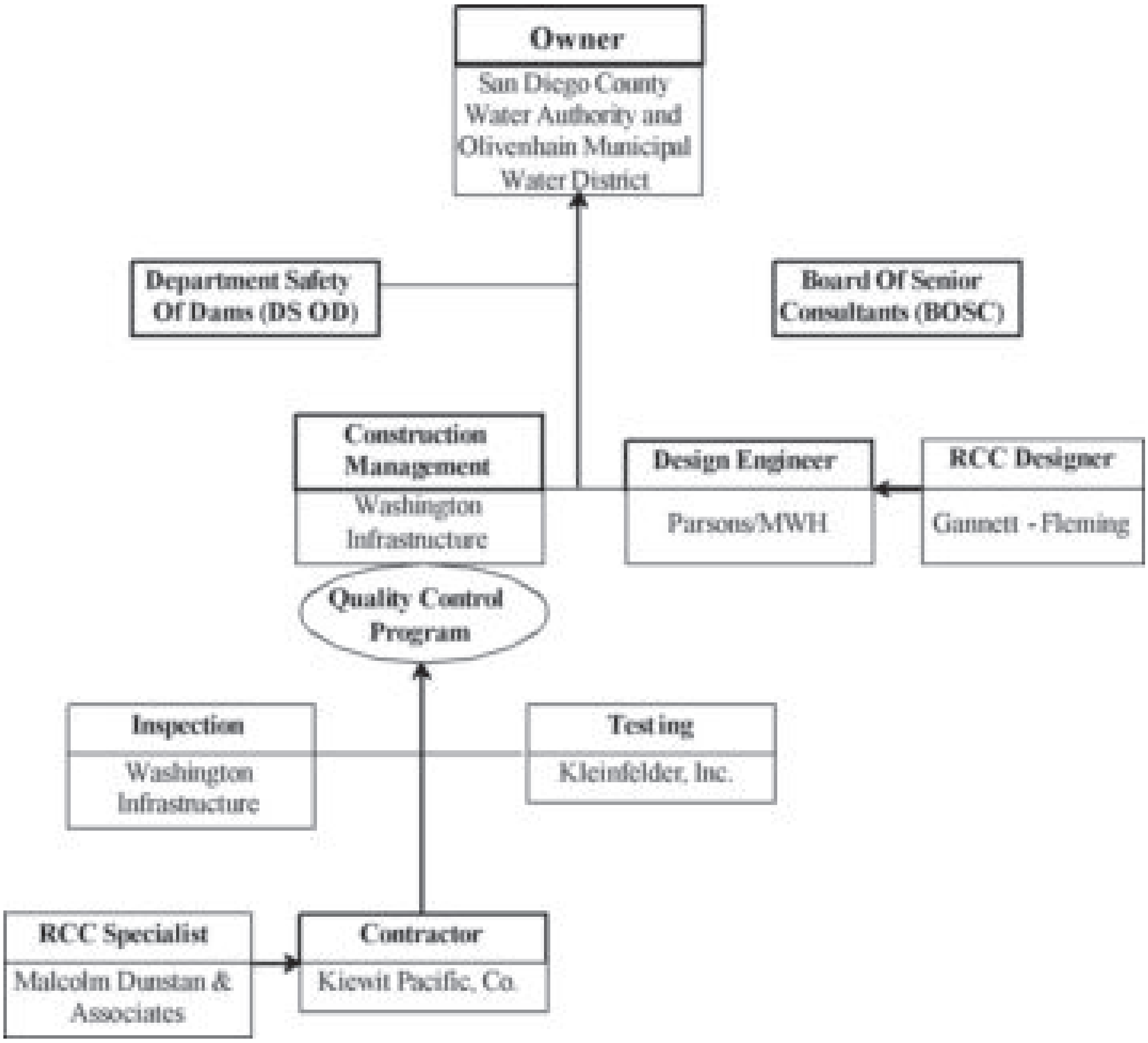

Fig. 13
Project Delivery System

The quarry inspector monitors the blasting operation of on-site materials. There are safety and operation procedures in place to ensure safety, environmental compliance, and the quality of the raw materials. The rock crushing plant inspector monitors the aggregate production and stockpile management and reports any irregularities during the manufacturing process. During rock production, laboratory technicians sample the materials and perform a series of tests to check the quality of materials. For the rock crushing plant inspector, the gradation test results are the most important information to evaluate the plant operation. If the gradations are not in compliance with the specifications, adjustments must be made to the plant to bring the gradations back into compliance. The batch plant inspectors monitor the proportions of concrete ingredients, workability, and temperature of the mix. The as-batched proportions of the ingredients are compared to the approved mix design proportions. They ensure that the aggregate moisture content is included in the proper free water content added to the mix to comply with the design water/cement

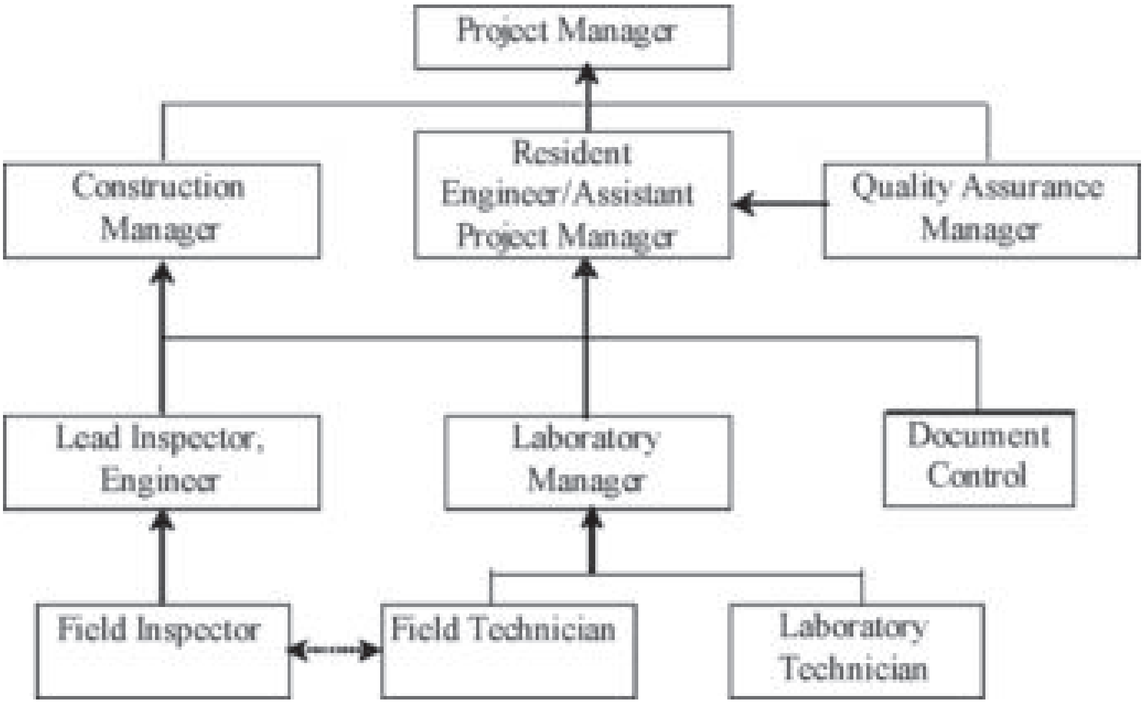

Fig. 14
Quality Control System

ratio. The batch plant inspectors receive the information on the workability and temperature of the mix from the field placement inspectors and verify the appropriate changes are made to the design mix if necessary.

The placement inspector monitors the contractor’s methodology and observes the workmanship. The placement inspectors are in continuous communication with the field technicians who perform a set of tests on the materials being placed. The field technicians inform the placement inspectors of the field test results. The inspectors compare their observations and the test results with the project specifications for compliance and direct changes to the operation if necessary. The primary elements that are monitored and documented on a RCC placement are the following: segregation of the mix during transport or placement, proper compaction and densities are achieved, the mix being placed has the proper workability (VeBe) and temperature, lifts are placed at the proper thickness and within the specified time allowances from the time the material is batched. Proper procedures are implemented to ensure full contact and bond with the abutments and the surfaces are kept moist, clean, and ready for the next lift to be placed.

The Construction Manager is primarily responsible for the coordination of field activities necessary to support the contractor’s construction activities. This position also handles interface and coordination with the Design Engineer and DSOD related to the Contractor’s construction activities.

The Resident Engineer is responsible for the overall QC program. He is responsible for the interpretation of the plans and specifications, interface with the Design Engineer to respond to Contractor questions related to the plans and specifications. He reviews all testing report and distributes it to the necessary entities. He also serves as the first line of contact to DSOD, The Design Engineer, and the Owner relative to questions or activities concerning the testing activities.

Table 14
Testing Responsibility Distribution

| Item | Testing | Test Method | Responsible Party | | |
|---|---|---|---|---|---|
| | | | Construction Management | Contractor | Supplier |
| RCC | VeBe Consistency | C 1170 | X | X | |
| | Density | C 1040 | X | X | |
| | Compressive Strength | C 39 | X | | |
| | Tensile Strength | CRD – C 164 | X | | |
| | Temperature | C 1064 | X | | |
| | Unit Weight | C 1170 | X | | |
| Aggregate | Gradation | C 136 | X | X | |
| | Moisture Content | C 566 | X | X | |
| | Particle Shape | D 4791 and CRD C 120 | X | | |
| | Abrasion | C 131 | X | | |
| | Atterberg Limits | D 4318 | X | | |
| | Lightweight Mat. | C 123 | X | | |
| | Clay Lumps and Friable Particles | C 142 | X | | |
| | - #200 Wash | C 117 | X | | |
| | Specific Gravity and Absorption | C 127 and C 128 | X | | |
| | Sand Equivalent | D 2419 | X | X | |
| Cement | Physical and Chemical Properties | | | | X |
| Fly Ash | Physical and Chemical Properties | | | | X |

In order to ensure that the information provided by the QC program was accurate, the Quality Assurance (QA) program monitors the QC program. The QA program is lead by a QA Manager who reports directly to the Project Manager. The QA monitors calibration of the equipments, sampling and testing procedures, plant and placement inspections. The QA Manager conducts audits and surveillances and reports the findings to the Project Manager and the Resident Engineer for corrective action.

The Project Manager for the Construction Management team has the ultimate responsibility for the overall QC/QA program.

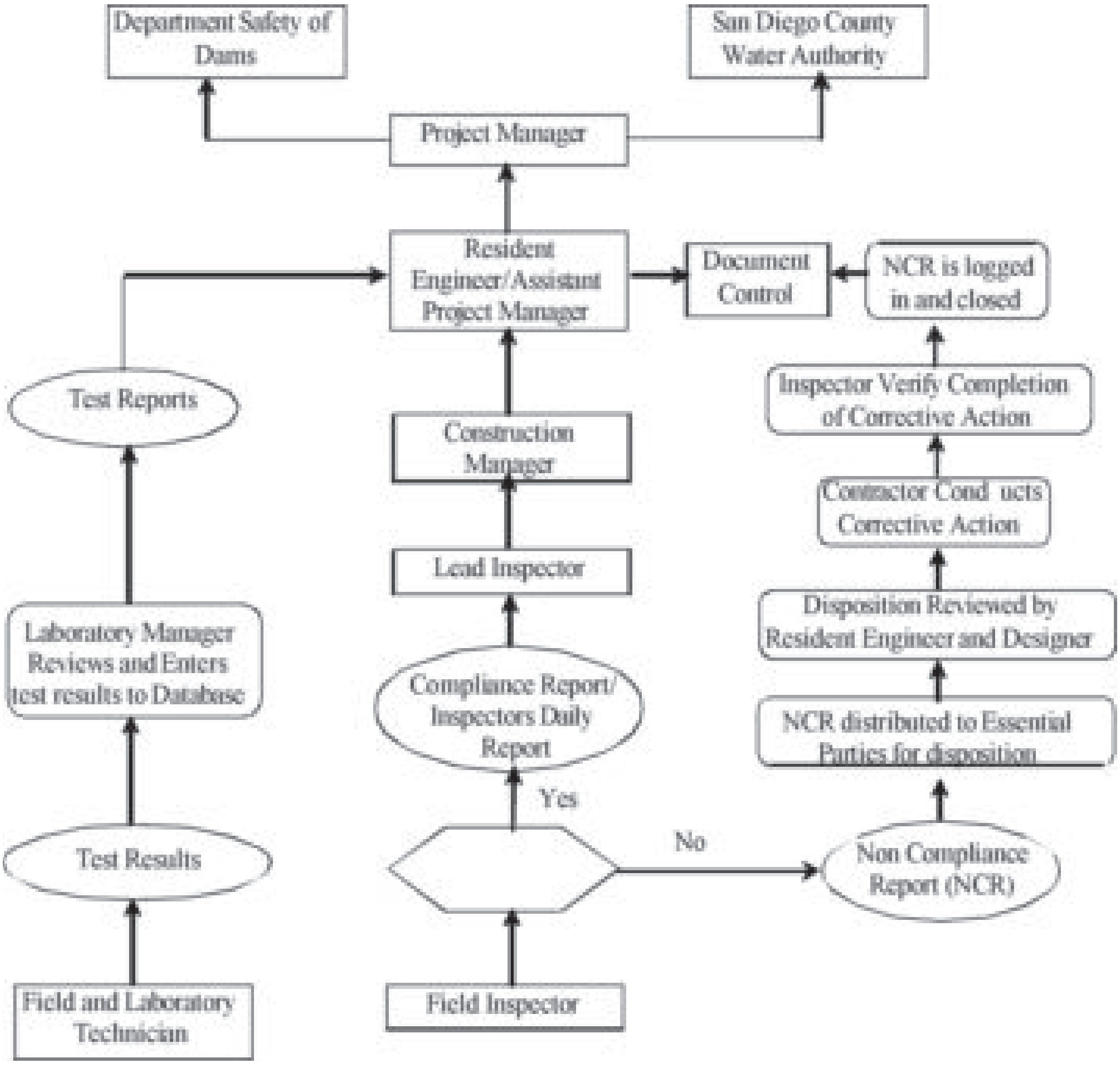

Fig. 15
Testing and Inspection Report Distribution

### 8.2.5. Official reporting

The test and inspection report distribution diagram is shown in Fig. 15. There are two types of testing: field and laboratory. Field test occurs during concrete or RCC placement. Field technicians perform a series of tests, record the test results, and inform the field inspectors. Laboratory tests are performed in the on-site QC laboratory. The Laboratory Manager reviews the test data before entering in the computer database. The computer database recalculates and stores the test data. The original test data are filed and at the end of the job these documents will go to Document Control. At the end of the day, the Laboratory Manager generates reports for the inspectors. Every week, the Laboratory Manager generates test reports. The Resident Engineer reviews the reports. After reviewing, the reports the reports are distributed to the Project Manager, DSOD, the Design Engineer and the Owner.

When inspector observes that the contractor's work complies with the project specification, the inspector writes a Daily Field Report (DFR). The DFR is then reviewed by the Lead Inspector and the Construction Manager. When the inspector observes deviations from the project specification, a non-compliance report (NCR) is generated and issued. The non-compliance report is distributed to the responsible party for the non-compliance report for evaluation and a recommended disposition. The Resident Engineer and Design Engineer review the recommended disposition. Upon approval from the Resident Engineer and/or Design Engineer, the Contractor conducts the corrective action. The inspectors verify the completion of the corrective action and issue a closed NCR. The NCR is reviewed by the Construction Manager, Resident Engineer, Project Manager, DSOD, and the Owner. If the NCR has modified the design documents it is then posted as a design change.

### 8.2.6. Tracking of concrete strength

Fig. 16 shows the chart developed to track the strength of the RCC built into the dam. The chart shows that the control of strength at 365-day maturity can be classed as good with a coefficient of variation of 12.9%. The results of the tests on specimens subjected to 7-day accelerated cure are shown to be a good guide to the 365-day strength. The coefficients of variations increase with lesser maturities and this is typical of high fly-ash mixes.

### 8.2.7. References

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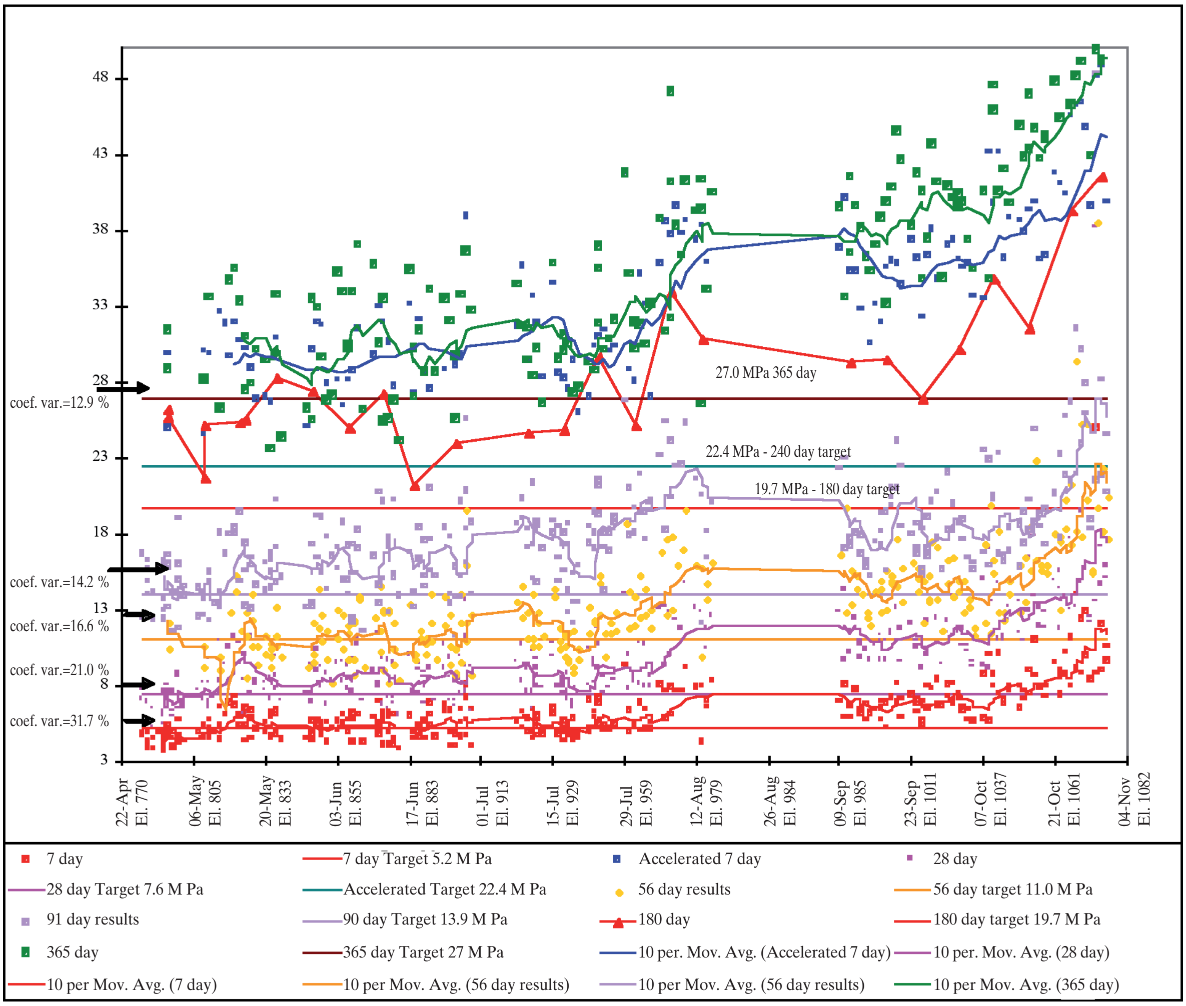


Fig. 16
Compression test results from quality control programme

## 8.3. ALQUEVA DAM

### 8.3.1. Introduction

Alqueva is a Portuguese multi-purpose scheme (hydropower, irrigation, flood control, economic development) located in the South of the country, on the river Guadiana, with a catchment of 48 500 km$^2$ in Spain and 6 500 km$^2$ in Portugal. The reservoir is 83 km long with a capacity of 4.15 × 109 m$^3$ of which 3.15 × 109 m$^3$ is live storage.

The dam is a double curvature arch with a maximum height of 96 m and 458 m crest length. The total volume of concrete is about 700 000 m$^3$. The dam body includes one bottom outlet, two mid-height orifices spillways and two surface spillways with three gates for a design flood of 12 000 m$^3$/s.

The total concrete volume for the scheme was about 1.23 × 106 m$^3$ including the dam abutments, the spillways structures and the powerhouse. This volume was placed between 1998 and 2002.

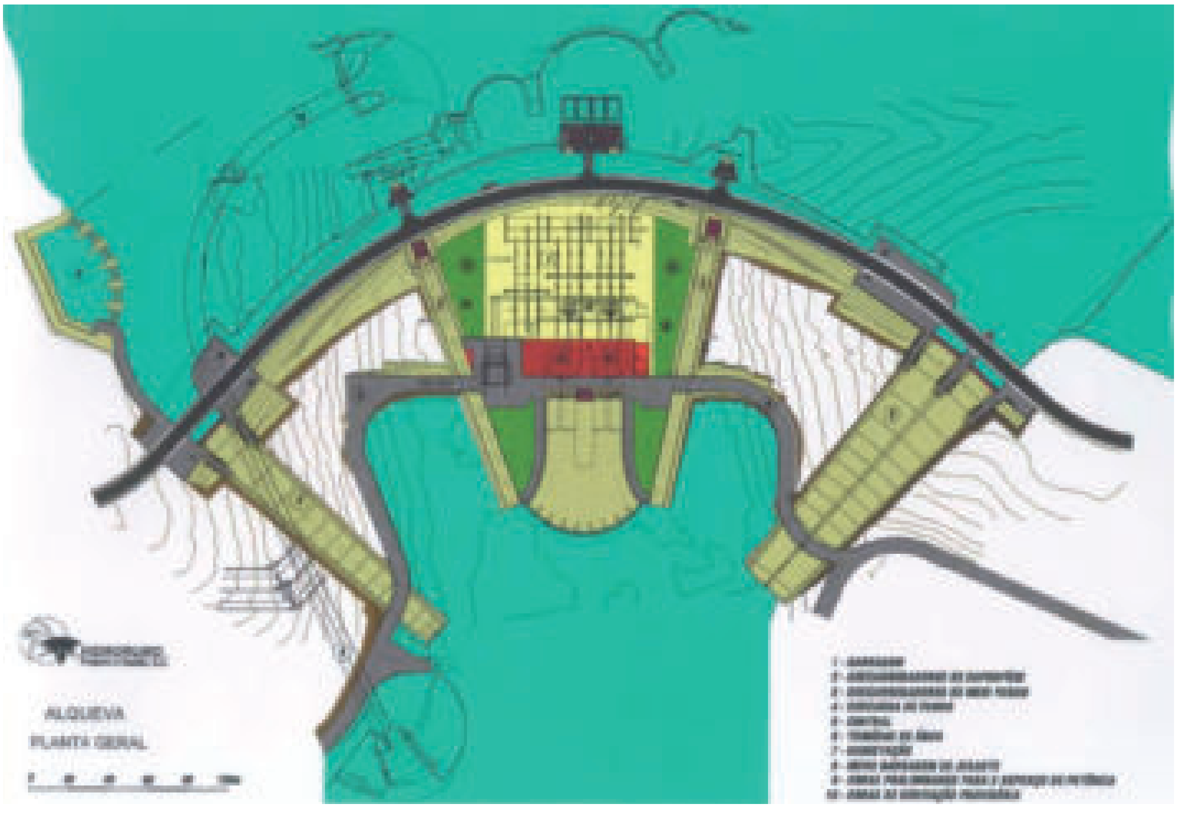
The Alqueva dam design was developed in several stages. The final stage lasted from 1992 to 1993, and the tender documents were finished in 1994. Impounding started in 2002.

### 8.3.2. Aggregate evaluation

The identification of possible sources for aggregates production started at the beginning of the feasibility studies (1972). At that time quarrying and gravel pits exploitation was considered as shown in Table 15. A quarry in the Green Schist was chosen because other rocks showed potential alkali-aggregate reactivity and/or excessive expansion, either in water or in sulphate solution, some of the potential quarries were too small and exploitation of gravel pits could not produce all required sizes of coarse and fine aggregates.

The quantities of aggregates estimated for concrete production were equivalent to 1 100 000 m$^3$, assuming 93% of for stripping and extraction efficiency. However, the environmental impact studies showed that the quarry location had to be changed so as not to be visible after filling the reservoir. This change gave an increased quantity of overburden excavation.

Because it was the first time that this green schist was to be used as concrete aggregate, a comprehensive evaluation was made of durability, including chemical and physical properties, with emphasis on alkali-silica reaction, sulphate attack, water expansion and absorption. The evaluation of mechanical properties included compressive strength, tensile strength, abrasion resistance and elastic properties. Because of the schistosity, anisotropic characteristics were determined by testing samples taken both along and perpendicular to the fabric. The rock was suitable as a source of aggregate except for freezing and thawing issue, which was not considered in the design because of the essentially frost-free southern location of the dam. This evaluation lasted from 1973 to 1977, when most of the diversion works were made using concrete produced with gravel pit aggregates.



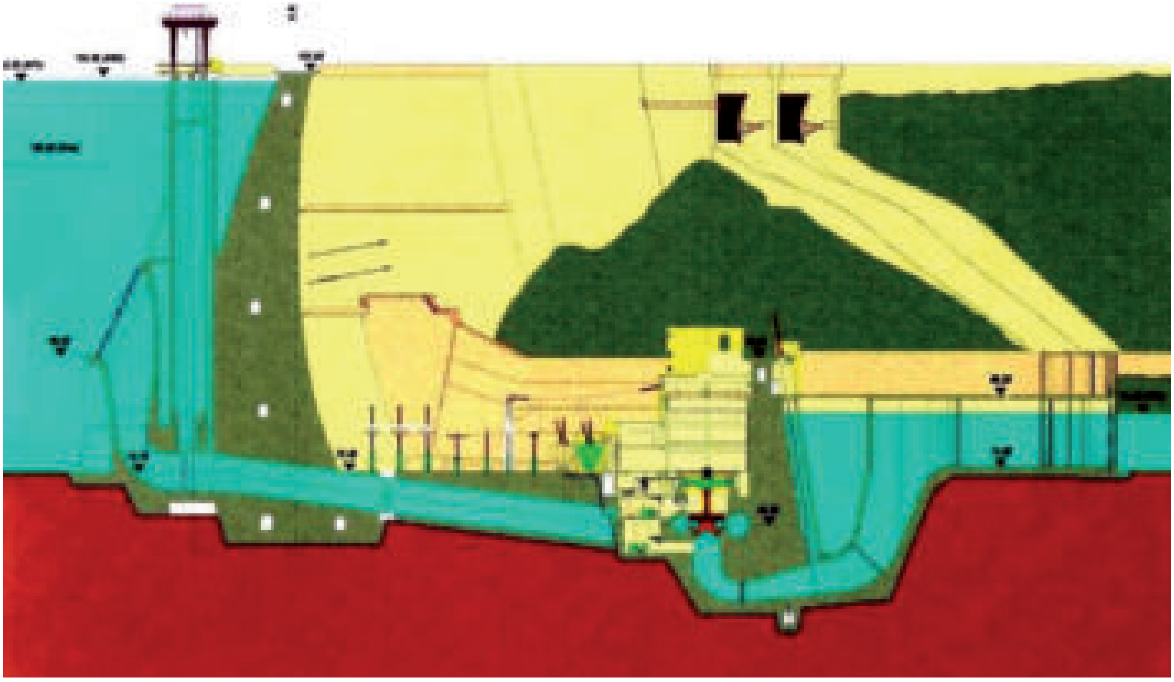


Fig. 17
Alqueva Dam layout

Crushing tests were done to evaluate the particle shape of the aggregates produced and losses during processing. The tests revealed an abnormal quantity of fines passing 0.15 mm sieve (22-25%). However, after normal processing it was possible to reduce the fines in order to obtain a good aggregate gradation.

Table 15
Locations identified as possible origin as raw materials for aggregate production

| Quarry sources | | | Gravel pits sources | | |
|---|---|---|---|---|---|
| **Type of rock** | **Distance from dam site (km)** | **Capacity** | **Location** | **Distance from dam site (km)** | **Capacity** |
| Green Schist | Right and left embankment (0.5 km to 1 km) | Enough volume for concrete production | Dejebe-Guadiana confluence | 2 km upstream. | Only for fine aggregates. |
| Marble | 2 km downstream | Enough volume for concrete production | Ardila-Guadiana confluence. | 10 km downstream | Only for fine aggregates. |
| Dolomitic limestone | 12 km by road | Enough volume for concrete production | Insua on the Guadiana river | 40 km by road | Not enough volume for coarse aggregates |
| Porphyry | 14 km by road | Volume not evaluated (*) | Brenhas- Ardila confluence | 10 km downstream | Only for fine aggregates |
| Gabro | 3 km | Not enough volume | | | |
| Granite | 40 km by road | Enough volume for concrete production | | | |
| Tonalite | 55 km by road | Volume not evaluated | | | |

(*) Alkali reactive rock.

The green schist was also evaluated on mortars produced with low heat cement (slag cement with 40% clinker and 55% of ground granulated blast-furnace slag) comparing strength, water demand, water absorption, capillarity and water expansion, with mortars moulded using siliceous sands. Later, tests were made with pozzolanic cement (60% clinker and 35% of class F pulverized fly ash). The influence of type and rate of admixtures on strength and on water demand of mortars were also evaluated in this phase.

### 8.3.3. Mix design and specification of concrete

The first phase of studies (1973/77) included the evaluation on concrete produced with 150 mm maximum size aggregate. In this phase compressive strength, tensile strength, elasticity and permeability were measured on cylindrical samples with 450 mm diameter by 900 mm high. The maximum water/cement ratios were respectively 0.60 and 0.55 in the core of the main dam and in the concrete used as upstream and downstream facing, In order to achieve these ratios, water reducing and plasticizing admixtures were used.

Because the works were interrupted during a period of 18 years, a second phase of tests on mortars and concrete were carried out with another type of cement, a pozzolanic cement with 35% of class F pulverized fly-ash. Tests performed to confirm the properties obtained in the first phase gave satisfactory results with as much as 20% of fly-ash blended into the pozzolanic cement. These studies allow the use of 200 kg/m$^3$ of total cementitious content in the body of the dam and 240 kg/m$^3$ in the faces of the dam. This means a total content of 104 kg/m$^3$ of cement and 96 kg/m$^3$ of fly-ash in the dam body and 125 kg/m$^3$ of cement and 115 kg/m$^3$ of fly-ash in the concrete faces, excepted in the upstream toe of the dam where the no fly-ash substitution was used because the tensile strength requirements given by earthquake loads. Permeability tests gave results which were low compared to similar projects ($1.80 \times 10^{-13}$ m/s)

The concrete mixes used on this project are shown in Table 16. As required by the specifications, the contractor had to provide samples of the aggregates, cements and fly ash for testing. These tests, including tests for selection of optimal admixtures and dosage rate, permit establishment of the mixes for concrete production.

When the results of inspection and tests at site showed changes in the quality of constituents, other mixes were provided to the contractor in order to accommodate this change and to achieve the concrete specification. If no accommodation was possible, the QC staff sent a non-conformity notice to S&M team in order to reject the respective constituents.

The mix designs were the responsibility of the design team and the contractor had to produce with the prescribed mixes. The tender document included specifications (according Portuguese and European standards) for aggregates production (quarrying, quality of rock extracted, gradation and specifications for delivery), water quality for concrete batching, admixtures, cement and fly-ash.

### 8.3.4. Concrete production

The planning of construction was done using a schedule of 8 months for erection of plant and 32 months for dam concreting followed by the spillways concreting. The schedule for concrete placement showed a requirement for about 2 000 $m^3$/day in two shifts of 10 hours. This required a 130 $m^3$/h cableway capacity which matched the capacity of the concrete plants. The formwork erection was carried out with tower cranes positioned on the dam block in order to leave cableways almost exclusively for concreting. Nevertheless, a second concrete plant was also considered to allow the construction for elements other than the dam and spillways. Both concrete plants had computer aided software developed by the team design (see below). All batch records were sent by radio transmission to a computer at the site laboratory.

Table 16
Mixes used in Alqueva project

| Strength | MSA (mm) | Consistency | Max. w/c ratio | Cementitious content (1) C+PFA (kg/$m^3$) |
|---|---|---|---|---|
| C12/15 | 150 | S1 | 0.60 | 160 + 40 |
| C12/15 | 75 | S1 | 0.55 | 192 + 48 |
| C16/20 | 75 | S1 | 0.55 | 240 + 0 |
| C20/25 | 75 | S2 | 0.50 | 290 + 0 |
| C16/20 | 38 | S2 | 0.50 | 330 + 0 |
| C20/25 | 38 | S2 | 0.50 | 400 + 0 |
| C20/25 | 19 | S2 | 0.50 | 420 + 0 |
| C35/45 | 19 | S2 | 0.40 | 500 + 0 |
| C30/37 | 10 | SCC | 0.40 | 550 + 0 |

(1) The cement is a pozzolanic type with 35% of PFA (pulverised fly-ash).

Because of the highest temperature rise during summer months, an ice plant of 15 t/h was required. A chilled water plant was also used to lower the hardened concrete temperature to 11ºC in order to start, as soon as possible, the grouting of the vertical joints in the dam. Concrete spreading and compaction was done with a small bulldozer and a battery of six 75 mm diameter vibrators attached the jib of an excavator which proved to be an efficient system.

During construction, several problems were identified. In the first year of concreting the cableways could not achieve the design capacity for transporting due to various factors. The cableway was supplement with Creter-Cranes.

The adopted impact-type of crushing equipment did not produce sufficient sand from the Green Schist and there was an over-production of medium size aggregate. This medium sizes aggregate had to be re-crushed, producing a large amount of fines (passing on 200 sieve) and reducing the aggregates production capacity.

The w/c ratios (water/cementitious) were established taken into account the medium aggressively of the river water to concrete durability, especially to calcium hydroxide. This was the reason for choosing a high fly ash content.

### 8.3.5. Project delivery system

Fig. 18 shows the entities involved in the project. Three main contracts were involved:

| | | |
|---|---|---|
| Contract C1 | Owner (EDIA) | – Team Designer (Electricity of Portugal – EDP Produção, Engenharia & Manutenção SA) |
| Contract C2 | Owner (EDIA) | – Surveying and Management Team, which includes the Quality Control (Electricity of Portugal – EDP Produção, Engenharia & Manutenção SA) |
| Contract C3 | Owner (EDIA) | – Contractor (ACE-Somague, Dragados, BPA, Necso) |

The C3 contract was awarded after international tender for dam and powerhouse construction.

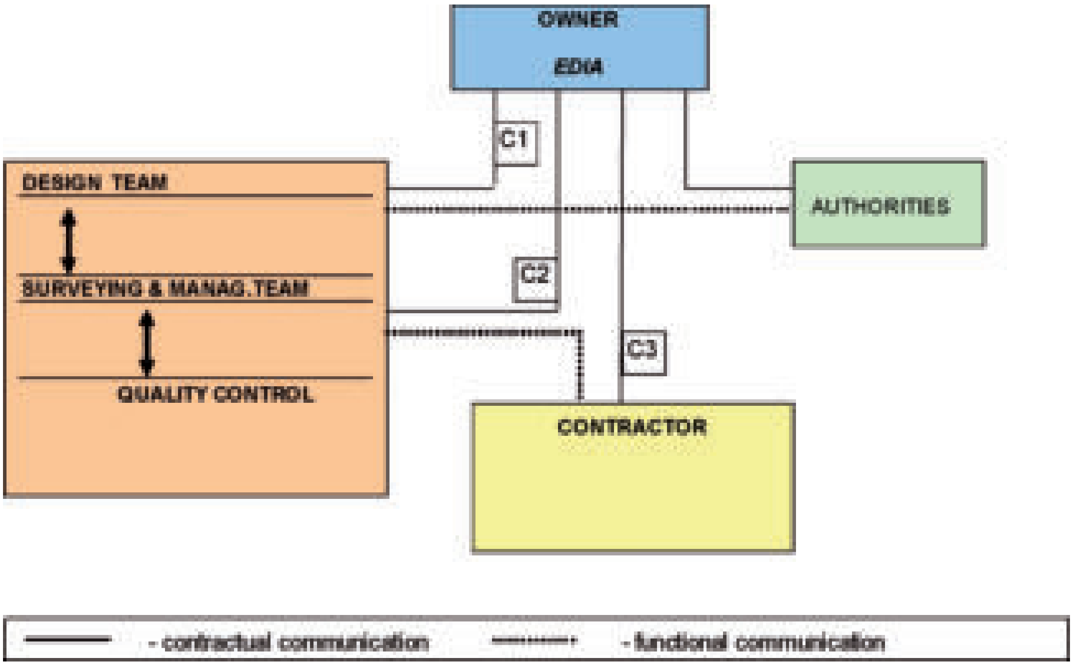


Fig. 18
Entities involved on Alqueva project

### 8.3.6. Quality Control System during dam construction

The plan for Quality Control in the C2 contract covered concrete production, transporting, placement, compaction, curing and testing for conformity evaluation. This plan was developed following the requirements of ISO 9002:1995.

The large number of tests required during construction justified the provision of a fully equipped site laboratory.

The QC system for Alqueva project included the following:

- Control of production processes by inspection of the equipment, particularly the concrete plant and the aggregates production plant

- Control by testing of the properties and inspection of the concrete constituents
- Control of concrete batching by inspection of loads cell deviation records, moisture content of fine aggregate and w/c ratio provide by batch-plant computer system
- Control of fresh concrete by sampling and testing
- Control of hardened concrete by testing samples and statistical analyses
- Control by inspection of the conditions for transporting, placing and consolidating concrete, including formwork and reinforcement.

### 8.3.7. Organization and responsibilities (communication)

Fig. 19 shows the organisation adopted in Alqueva project, and included in the QC plan. The continuous lines represent the hierarchical relations and the stippled lines show communications necessary for QC activities.

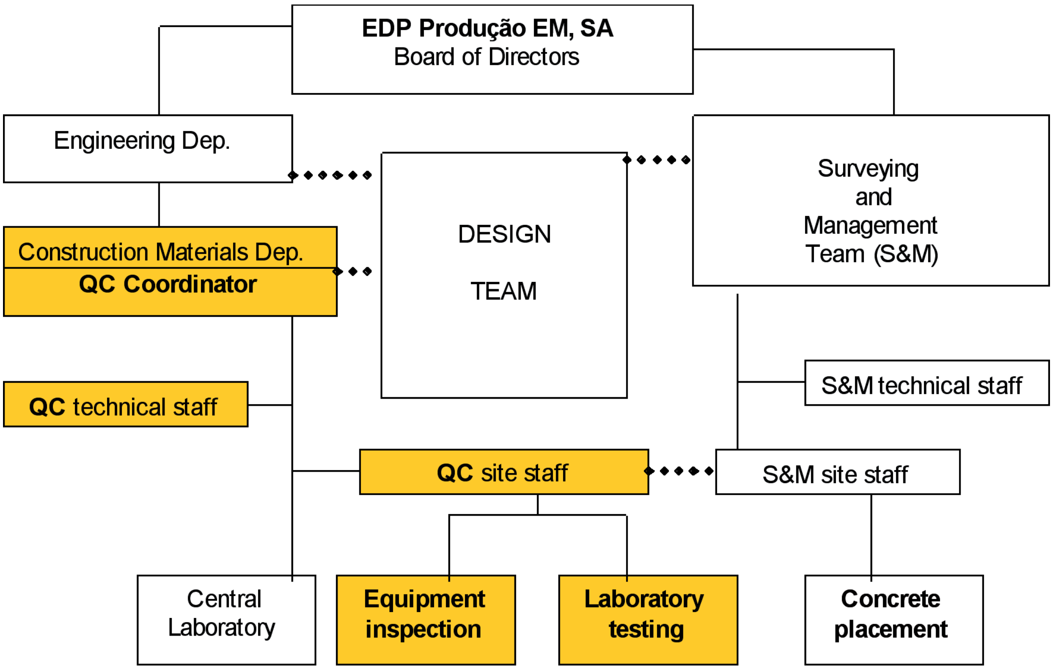


Fig. 19
Organisation chart of the design company
(QC staff shown in yellow)

The Engineering Department and the Surveying and Management (S&M) Team are governed directly by the Board of Directors. The Design Team staff came from the Engineering Department.

The QC staff at job site were organised under the Construction Material Department. The S&M team at the site made all inspection of concrete placement and consolidation.

Because the communication between S&M and the contractor comes under the C2 contract, the QC staff communicated directly only with the S&M team who sent all non-conformity notices to the contractor.

In the QC plan, the responsibilities and obligations of the staff were fully described.

### 8.3.8. Quality Control planning

The flow diagram of the QC plan is shown in Fig. 20 and shows the scope of the inspection and testing. This diagram represents the main quality system applied on this project. All actions had written procedures which establish by whom, how, when and what must be done. Each procedure and testing plan was recorded in order to ensure traceability of all non-conformities. Each non-conformity was immediately communicated to the S&M staff.

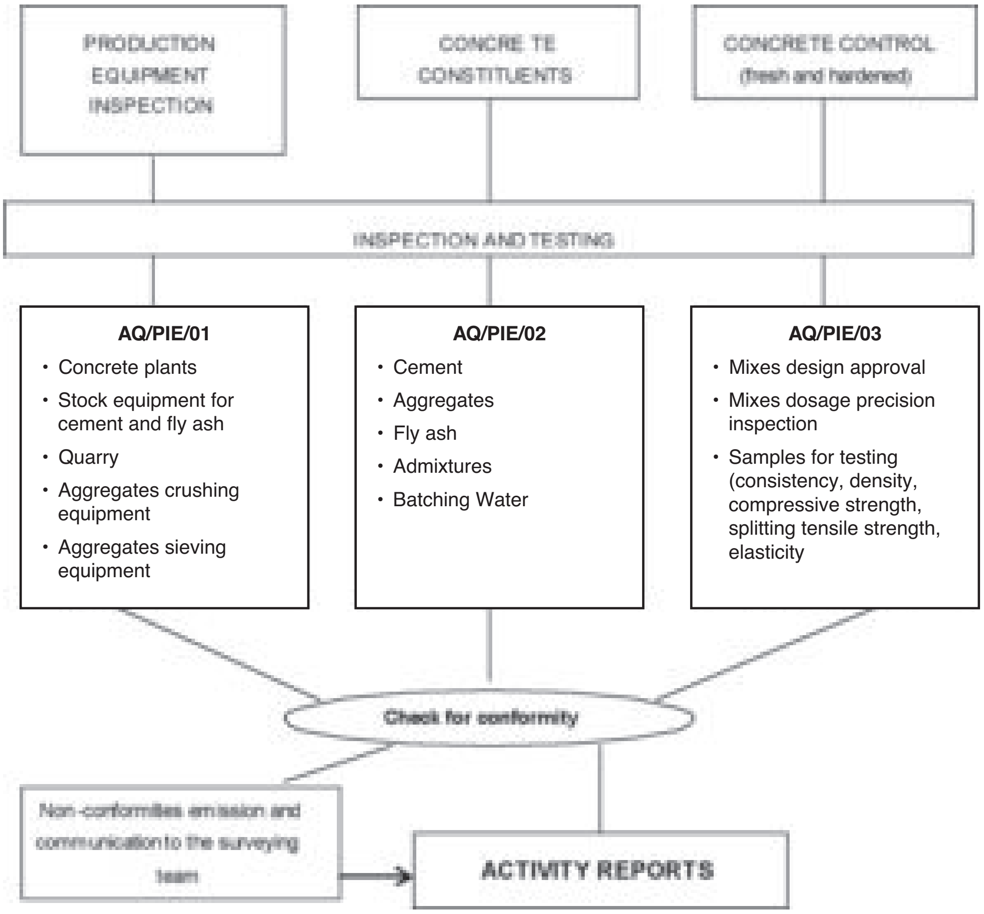


Fig. 20
The organisational diagram for the QC plan

### 8.3.9. Process control (concrete production, placement and cure)

The process control was mainly applied to concrete production, transport, placement and curing. The concrete plant software sends data in real time by radio transmission to the computer in the laboratory which permits automatic control of concrete production. Each day QC staff verifies the load cell deviation of each constituent in all batches of the day. The computer software can be configured to give an alarm if the maximum allowable deviations are exceeded and stop production.

The software inputs of each batch contained the mix number, the code number and concreting level of the works (block of the dam or spillway, element of the powerhouse, etc), date and hour, number of concreting authorisation. Every batch register included the design and actual weights of the mix, and automatically calculated the deviation of each constituent.

This software allowed statistical analyses of all batches according to time interval, type of mix, location of placement, etc. and the respective volumes of concrete production.

Each sample obtained for QC control was also registered in the computer with the records of the respective batch.

S&M staff issued the authorisation number for concreting, after an overall inspection of the works. This inspection included type, number and quality of the concreting equipment, workmanship and analyses of possible adverse concrete conditions. Also reinforcement, formwork and the number and position of monitoring equipment or other embedded items were inspected.

During the concreting, the S&M staff made records of temperature, workability at the placement, time of concreting, and any interruptions to concreting with causes.

### 8.3.10. Tests and inspection

For testing and inspection three main plans (PIE) where provided (see Table 17)

- equipment control (PIE 01)
- testing and inspection of the concrete constituents (PIE 02), and
- production and properties control of fresh and hardened concrete (PIE 03)

Each PIE showed what material, equipment or issue related to the concrete had to be controlled, the objective of this control, the type and frequency of inspection or tests required, acceptance criteria, who was responsible and the records to be made and where they must be kept.

In Table 18 and Table 19 are presented compressive strength results, moduli of elasticity and grading of the aggregates. Compression strength on cube specimens for mixes with MSA higher than 38 mm were correlated with the results from cylinders of 450 mm diameter and 900 mm height and the results from 200 mm cube with 38 mm MSA concrete.

### 8.3.11. Non conformity control

If a non-conformity was discovered in the course of inspection or testing, the QC staff issued a notice which registered the nature, cause and time of the occurrence. This notice could be:

- Type I – for minor non-conformities; and
- Type II – for unusual and serious non-conformities.

Type II documents were only issued by the coordinator of the QC control.

Table 17
Tests and inspections for Alqueva project

| PIE 01 | | PIE 02 | | PIE 03 | |
|---|---|---|---|---|---|
| **Equipment** | **Inspection** | **Constituents** | **Test./Inspect.** | **Concrete** | **Test./Inspect** |
| Crushing | Opening of the jaw crusher | Cements | Furnish documents | Fresh concrete | Temperature, consistency |
| Sieving | Visual inspection of sieves | Cement – conformity to EN 197 EN 196 | setting time, strength, expansibility, sulphates, chlorides, pozzolanic activity | | Visual inspection of segregation, cohesion, bleeding, and spec. weigh |
| Aggregates stock | Systems aggregates transporting at stockpiles and silos | Cements – conformity as specifications EN 196 | Blaine, LOI, magnesium oxides, Equiv. alkalis, heat of hydration | Hardened concrete | Spec. weigh, Compressive and splitting tensile strength and elasticity as DIN 1048 |
| Cement silos | Visual inspection (filters, waterproofing, etc) | Fly Ash As EN 450 /1 | Fineness, Expansibility, spec. weigh, activity index, LOI, free CaO , chlorides, $SO^3$ | Sprayed concrete | Rebound, compressive strength as ASTM C42 in cores |
| Concrete Plant software | The mixes used are correct | Admixtures | Furnish documents, | Grouts for dam vertical joints | Rheology setting bleeding and strength |
| Dosage of concrete constituents | Load cells calibration | Admixtures as EN 934 | Spec. weight, solid content,, pH, IR spectrum | | |
| | Visual inspection when working | Aggregate | Visual inspection at quarry | | |
| | Tests of cubic meter | | Grading tests | | |
| | Precision of dosage | | Specific weigh and absorption | | |
| | Tests of dry grading | | Volumetric index | | |
| | | | Humidity of sands | | |
| | | | L.A. abrasion | | |
| | | Batching water | pH, Oxygen consumption, | | |
| | | | Chlorides | | |
| | | | Residue | | |
| | | | Strength in mortars | | |

Table 18

Results of Compression Strength and Modulus of Elasticity

| **Type of concrete (see Table 16)** | **Medium Compression Strength (1)** | | | | | | **Modulus Elasticity at 1 year (GPa)(2)** |
|---|---|---|---|---|---|---|---|
| | **90 days** | | | **1 year** | | | |
| | **Nº samples** | **Cube str. (MPa)** | **Coef. Var. (%)** | **Nº samples** | **Cube str. (MPa)** | **Coef. Var. (%)** | |
| C12/15 - 150-S1-0,60 | 374 | 24.0 | 21.3 | 369 | 35.4 | 13.6 | 25.8 |
| C12/15 - 75-S1-0,55 | 172 | 22.8 | 20.1 | 152 | 34.4 | 12.4 | 27.6 |
| C16/20 - 75-S1-0,55 | 176 | 26.6 | 17.1 | 150 | 35.1 | 14.5 | 29.7 |
| C20/25 - 75-S2-0,50 | 126 | 34.4 | 14.2 | 112 | 42.2 | 11.3 | 32.7 |
| C16/20 - 38-S2-0,50 | 110 | 33.6 | 14.5 | n.d. | n.d. | n.d. | n.d. |
| C20/25 - 38-S2-0,50 | 271 | 42.0 | 13.1 | n.d. | n.d. | n.d. | n.d. |
| C20/25 - 19-S2-0,50 | 26 | 41.0 | 12.3 | n.d. | n.d. | n.d. | n.d. |

(1) Compression strength was evaluated on 200 mm cubes. For MSA 150mm and 75mm cubes were moulded with 38 mm sieved concrete.

(2) Modulus of elasticity was evaluated on cylinders of 450 mm diameter and 900 mm height of non sieved concrete.

n.d. Not determined.

Table 19

Results of Aggregates Gradation (U.S. standard sieves)

| **Coarse aggregates** | | | | | |
|---|---|---|---|---|---|
| Gradation class (mm) | Nº of samples | % retained (average values) | | | |
| | | Over grading | In class | Sub grading ≥ 0,15mm | Sub grading < 0,15mm |
| 75 - 150 | 190 | 0.0 | 72.7 | 27.0 | 0.3 |
| 38 - 75 | 191 | 3.8 | 75.8 | 19.8 | 0.6 |
| 19 - 38 | 245 | 1.3 | 68.6 | 29.1 | 1.0 |
| 9.5 - 19 | 245 | 2.4 | 89.2 | 7.6 | 0.8 |
| 4.75 - 9.5 | 245 | 16.3 | 74.4 | 8.4 | 0.9 |
| 2.36 - 4.75 | 245 | 13.5 | 71.6 | 14.2 | 0.6 |
| **Fine aggregates** (0 – 2.36 mm) % retained | | | | | |
| Sieve #8 | Sieve #16 | Sieve #30 | Sieve #50 | Sieve #100 | Sieve #200 |
| 9.1 ± 1.3 | 31.1 ± 7.5 | 22.5 ± 4.9 | 14.7 ± 3.6 | 10.5 ± 3.3 | 6.4 ± 3.6 |

All non-conformity notices were sent to the S&M staff. A response to the non-conformity notice was proposed by the contractor and discussed with S&M staff. Sometimes the Design Team are also involved in this process.

### 8.3.12. Test equipment control

The QC plan included a complete list of laboratory equipments required at the site with requirements for calibration of the equipment and maintenance.

### 8.3.13. Quality control reports and statistical analyses

Every inspection and test were recorded and placed in archives which remained at the site laboratory. All the results were also stored in the computer for statistical analyses which results are exported to the activities reports.

### 8.3.14. Activity reports

Every three months the technical staff of the QC control issued reports with all activity registered. The objective was provide this information to the owner and to the authorities.

# 9. REFERENCES

**Various**

| | |
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| 21. | The Contractor's Guide to Quality Concrete Construction, 3rd ed, 2005. | |
| **American Society for Testing and Materials (ASTM)** | | |
| 22. | ASTM C31 | Practices for making and curing concrete test specimens in the field. |
| 23. | ASTM C33 | Specification for concrete aggregates. |
| 24. | ASTM C39 | Test method for compressive strength of cylindrical concrete specimens. |
| 25. | ASTM C40 | Test method for organic impurities in fine aggregates for concrete. |
| 26. | ASTM C42 | Methods of obtaining and testing drilled cores and sawed beams of concrete. |
| 27. | ASTM C88 | Test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate. |
| 28. | ASTM C109 | Test method for compressive strength of hydraulic cement mortar (using 2-in. or 50-mm cube specimens). |
| 29. | ASTM C117 | Test method for materials finer than 75 mm (No. 200) sieve in mineral admixtures by washing. |
| 30. | ASTM C127 | Test method for specific gravity and absorption of coarse aggregate. |
| 31. | ASTM C131 | Test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine. |
| 32. | ASTM C136 | Method for sieve analysis of fine and coarse aggregates. |
| 33. | ASTM C142 | Test method for clay lumps & friable particles in aggregates. |
| 34. | ASTM C143 | Test method for slump of Portland cement concrete. |
| 35. | ASTM C150 | Standard Specification for Portland Cement. |
| 36. | ASTM C151 | Test method for autoclave expansion of Portland cement. |
| 37. | ASTM C172 | Standard Practice for Sampling Freshly Mixed Concrete. |
| 38. | ASTM C173 | Test Method for air content of freshly mixed concrete by the Volumetric method. |
| 39. | ASTM C186 | Test method for heat of hydration of hydraulic cement. |
| 40. | ASTM C188 | Test method for density of hydraulic cement. |

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|---|---|---|
| 41. | ASTM C192 | Making and curing concrete test specimens in the laboratory. |
| 42. | ASTM C 227 | Test method for potential alkali reactivity of cement – aggregate combinations (mortar bar method). |
| 43. | ASTM C 331 | Test method for air content of freshly mixed concrete by the pressure method. |
| 44. | ASTM C 232 | Test method for bleeding of concrete. |
| 45. | ASTM C 260 | Specification for air-entraining admixtures for concrete. |
| 46. | ASTM C 289 | Test method for potential alkali silica reactivity of aggregates (chemical method). |
| 47. | ASTM C 311 | Method for sampling and testing fly ash or natural pozzolans for use as a mineral admixture in Portland cement concrete. |
| 48. | ASTM C 411 | Test method for effectiveness of mineral admixtures in preventing excessive expansion of concrete due to the alkali-aggregate reaction. |
| 49. | ASTM C 451 | Test method for early stiffening of Portland cement (Paste method). |
| 50. | ASTM C 494 | Specification for chemical admixtures for concrete. |
| 51. | ASTM C 618 | Specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in Portland cement concrete. |
| 52. | ASTM C 827 | Test method for early volume change or cementitious mixtures. |
| 53. | ASTM C 989 | Specification for ground iron blast-furnace slag for use in concrete and mortars. |
| 54. | ASTM C 1064 | Standard test method for temperature of freshly mixed Portland cement concrete. |
| 55. | ASTM C 1077 | Standard practice for laboratories testing concrete and concrete aggregates for use in construction and criteria for laboratory evaluation. |
| 56. | ASTM C 1078 | Standard test methods for determining the cement content of freshly mixed concrete. |
| 57. | ASTM C 1079 | Standard test methods for determining the water content of freshly mixed concrete. |
| 58. | ASTM C 1170 | Determining the consistency and density of roller-compacted concrete using the vibrating table. |
| 59. | ASTM C 1260 | Test method for potential alkali reactivity of cement – aggregate combinations (mortar bar method). |

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| 61. | ASTM D 2419 | Test method for sand equivalent value of soils and fine aggregate. |
| **British Standards (BS)** | | |
| 62. | BS l46: 2002 | Specification for Portland blast-furnace cements with strength properties outside the scope of BS EN 197-1. |
| 63. | BS 882 | Specification for Aggregates from Natural sources. |
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| 65. | BS 8110-1:1997 | Structural use of concrete. Code of practice for design and construction. |
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| 66. | BS EN 97-1:2000 | Cement Composition, specifications and conformity criteria for common cements. |
| 67. | BS EN 206-1:2000 | Concrete. Specification, performance, production and conformity. |
| 68. | BS EN 1008: 2002 | Mixing water for concrete. |
| 69. | BS EN 13139: 2002 | Aggregates for mortar. |

# APPENDIXES 1

## TABLES OF TYPICAL TEST FREQUENCIES

Table A1-1

Table 6.1 from Bulletin 126, State of the art pf RCC

| Material tested | Test procedure | Test Standard[1] | Frequency[2] |
|---|---|---|---|
| Cement | Physical and chemical properties | ASTM C150 | Manufacturer's certificate or pre-qualification |
| Pozzolan | Physical and chemical properties | ASTM C618 | Manufacturer's certificate or pre-qualification |
| Admixture | | ASTM C494<br>ASTM C128 | Manufacturer's certificate |
| Aggregates | Relative Density And Absorption | ASTM C127<br>ASTM C128 | One per month or 50 000 $m^3$ |
| Aggregates | Flat and elongated particles | BS812 | One per month or 50 000 $m^3$ |
| Aggregates | Los Angeles Abrasion | ASTM C131 | One per month or 50 000 $m^3$ |
| Aggregates | Gradation | ASTM C117<br>ASTM C136 | One per shift or One per day |
| Aggregates | Moisture content | ASTM C566<br>ASTM C70 | Before each shift or as required |
| RCC | Workability | ASTM C1040 | 500 $m^3$ or as required |
| RCC | Gradation | ASTM C117<br>ASTM C 136 | 1000 $m^3$ or as required |
| RCC | Fresh density | ASTM C1040 | 1000 $m^3$ or as required |
| RCC | Oven-dry Moisture content | ASTM C566 | 1000 $m^3$ or as required |
| RCC | Temperature | ASTM C1064 | 100 $m^3$ or as required |
| RCC | Variability of Mixing procedures | ASTM C172, C1078, C1079 or special | Two per month or 25 000 $m^3$ |
| RCC | Compressive Strength | ASTM C1176 or tamper | Two per day or 1000 $m^3$ |
| RCC | Tensile strength (direct and/or indirect) | Special or ASTM C496 | One per day or 2000 $m^3$ |
| RCC | Elastic modulus | ASTM C469 | One per day or 2000 $m^3$ |

Notes: 1. Or other appropriate Standard.
2. Frequency will be dependant upon the size of project and the degree of control required.

# Table A1-2A

## Typical testing for medium size RCC dam

| S.No | Activity | Inspection / Test method | Instrument used | Acceptance Criteria | Ref. Standard | Sampling plan | Frequency | Testing Agency | Quality record | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| **Receiving Inspection and Testing** | | | | | | | | | | |
| **1** | **Cement** | | | | | | | | | |
| (a) | Grade & Date of Manufacturer | Visual Inspection | Nil | Cement should be greater than or equal to required grade & date of manufacture should be less than 3 months. | IS:269-1976<br>IS:1489-1989 Part-ii | 1 in 50 | Every batch | In- House | GRN,Test Ceertificates | Store Incharge |
| (b) | Weight | Verification of weight | Spring balance | +/- 1.0 Kg | nil | 1 in 50 | Every batch | In- House | GRN | Store Incharge |
| (c) | Std consistency of cement | Vicats test | V'cats apparatus | 24 to 35 % of water by wt. of cement | IS:4031-1968 | 1 in 50 | Every batch/ Week/per 500 MT | In- House | Cement testing register | QC incharge |
| (d) | Initial & final setting time | Vicats test | V'cats apparatus | Initial time= >30min Final time= <600 min | IS:12269-1987<br>IS:4031-1968 | 1 in 50 | Every week/per 500MT | In- House | Cement testing register | QC incharge |
| (e) | Compressive Strength of Cement | as per IS:4031-1968 | Vibration, M/c,mould,comp.test machine | Table No. IS:4031-1968 IS:650-1966 | IS:4031-1968<br>IS:650-1966 | 1 in 50 | Every batch/ Week/per 500 MT | External / in house | Test certificates/ Cement testing file | QC incharge |
| (f) | Fine ness. of cement. | Sieve analysis | 90 micron sieve,weight,balance | Residue left by wt of fines < 10% | IS:269-1976 | 1 in 100 | Every batch/ Week/per 500 MT | In- House | Cement testing file | QC incharge |
| (g) | Soundness Test. | Boiling test | Le' chatelier apparatus | Expansion < 10mm | IS:5514-1969 | Random | Monthly/Per 500MT | In- House | Cement testing file | QC incharge |
| (h) | Specific gravity | Le' chatlier test | Le' chatelier flask | 3.1 to 3.15 | IS: 4031-1968 | 1 in 50 | Weekly or per 500MT | In- House | Cement testing file | QC incharge |
| (I) | Fineness of cement | Blain's test | Blain's air permiabilty appartus | More than 2250 Sq.cm/gm | IS: 4031-1968,IS:269-1976 | 1 in 50 | Weekly or per 500 MT | In- House | Cement testing file | QC incharge |
| **2** | **Sand** | | | | | | | | | |
| (a) | Silt Content | Sedimentation Method | Measuring Cylinder | Max 8% in 10 min | IS:2386-1963 part -ii | Random | Per Truck/ Weekly | In- House | Sand testing file & GRN | QC incharge |
| (b) | Moisture Content | Drying/Weighing or by visual inspection | Weight balance, hot plate or Aquameter | nil | IS:2386-1963 | Every Pour | Per Truck/ Twice in a day while concreting | In- House | Sand testing file | QC incharge |
| © | Deletorious Substances | as per IS:2386-1963 - Part-II | | 5% of by weight of F.A | IS:2386 | Random | For change of source or six month | External | Test certificate | QC incharge |
| (d) | Finenens Modulus | Sieve analysis | IS:sieves | FM : 2.5 to 3.5 for N.sand & FM: 2.2 to 3 for C.sand | IS:2386-1963/ Tech. Specification Vol-II | Random | Weekly/ At the time of production from crusher | In- House | Gradation File. | QC incharge |
| (f) | Specific gravity & water absorption | IS:2386-1963 Part-III | Pycnometer | -- | IS:2386 part iii | Random | Monthly or Change of source. | In- House | Sp. Gr. Of F.A. and C.A. file. | QC incharge |
| (h) | 75 mic wash | Washing test | IS:sieves | Not more than 15% | Technical Sp.Vol.-II | Random | Monthly | In- House | Sand testing file | QC incharge |

## Table A1-2B
## Typical testing for medium size RCC dam

| S.No | Activity | Inspection / Test method | Instrument used | Acceptance Criteria | Ref. Standard | Sampling plan | Frequency | Testing Agency | Quality record | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| **3** | **Coarse Aggregates** | | | | | | | | | |
| a | Size, Shape,and texture | Visual Inspection | --- | | IS:383-1970 | Random | Every dispatch forthnightly | In-house | | QC Incharge |
| b | Specific gravity & water absorption | IS:2386 Part-III | Density Basket, Balance, oven | > 2.7 | IS:383-1970<br>IS:2386 | Random | Every dispatch forthnightly | In-house | Coarse aggregates testing file. | QC incharge |
| c | Gradation | Sieve analysis | IS:sieves | Table 2 &5 | IS:383-1970/ Tech. Spect. Vol-II | Random | Every dispatch forthnightly | In-house | Grtadation File. | QC incharge |
| d | Impact Test | As per IS:383 | Impact Test Machine | <45% by wt of aggregates for non waring surface | IS:383-1970 | Random | Every change of source/ Once in a Month | In-house | Coarse Agg. testing file | QC incharge |
| e | Crushing test | As per IS:383 | Comp. Testing machine | <45% by wt of aggregates for non waring surface | IS:383-1970 | Random | Every change of source/ Once in a Month | In-house | Coarse Agg. testing file | QC incharge |
| f | Abrassion test | As per IS:383 | Los Angles machine | <45% by wt of aggregates for non waring surface | IS:383-1971 | Random | Every change of source/ Once in a Month | In-house | Coarse Agg. testing file | QC incharge |
| h | 75 mic wash | As per IS:384 | IS:sieves | < 15 % | IS:383-1972 | Random | Every change of source/ Once in a Month | In-house | Coarse Agg. testing file | QC incharge |
| I | Flakiness and Elongation Index. | As per IS-2386 | IS-sieves and metal gauges. | < 25% for RCC. | IS-2386 Part-I | Random | Every change of source/ Once in a Month | In-house | Coarse Agg. testing file | QC incharge |
| **4** | **Steel** | | | | | | | | | |
| (a) | Tensile strength Fe 415/Fe 250. | Tensile Test | UTM | 4565 to 4850 Kg/cm | IS:1786-1985 | 10 MT | Every change of manufacturer/ Six month | External | Test certificates | QC incharge |
| (b) | Bending | Bend Test | UTM | | IS:1786-1985 | 10 MT | Every change of manufacturer/ Six month | External | Test certificates | QC incharge |
| © | Rebending | Rebend Test | UTM | | IS:1786-1985 | 10 MT | Every change of manufacturer/ Six month | External | Test certificates | QC incharge |
| (d) | Elongation | Elongation test | UTM | < 14.5% for Fe 415<br>< 12% for Fe 500 | IS:1786-1985 | 10 MT | Every change of manufacturer/ Six month | External | Test certificates | QC incharge |

## Table A1-2C

## Typical testing for medium size RCC dam

| S.No | Activity | Inspection / Test method | Instrument used | Acceptance Criteria | Ref. Standard | Sampling plan | Frequency | Testing Agency | Quality record | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| **5** | **Water** | | | | | | | | | |
| (a) | Sulphate Test | Soluble Test packs | test packs | <400 ppm | IS:3025-1964<br>IS: 456-2000 | Random | Weekly | In house | Water Testing File | QC incharge |
| (b) | Chloride Test | Soluble Test packs | test packs | < 2000 ppm | IS:3025-1964<br>IS: 456-2000 | Random | Weekly | In house | Water Testing File | QC incharge |
| © | Hardness Test. | Soluble Test packs | test packs | | IS:3025-1964<br>IS: 456-2000 | Random | Weekly | In house | Water Testing File | QC incharge |
| (d) | PH valve. | Soluble Test packs | test packs | 7 to 8 | IS:3025-1964<br>IS: 456-2000 | Random | Weekly | In house | Water Testing File | QC incharge |
| **6** | **Admixtures** | Visual | ----- | should be within shelf life | ---- | Random | Every purchase | In house | GRN and Test Certificates. | QC incharge |
| **7** | **Flyash** | | | | | | | | | |
| (a) | Chemical tests | ASTM | | | IS-1727-1967 | Randomly | Per 1000 MT. | External | Test Certificates. | QC incharge |
| (b) | Specific Gravity | ASTM | Le-Chetlier flask | 2.1 to 3.0 | IS-1727-1968 | Randomly | Per 1000 MT. | External | In house | QC incharge |
| (c ) | Fineness of Fly Ash | Blain's Method | Blain's air permiability apparatus | > 2500 Cm2/Gm. | IS-1727-1969 | Randomly | Per 1000 MT. | External | In house | QC incharge |
| (d) | Lime rectivity test | Comp. Strength test | Lime rectivity apparatus | 4.0 N / mm2 | IS-1727-1970 | Randomly | Per 1000 MT. | External | Test certificates. | QC incharge |
| (e) | Soundness by auto clave method. | Auto Clave method. | Auto Clave apparatus | < 0.18% | IS-1727-1971 | Randomly | Per 1000 MT. | External | Test certificates. | QC incharge |
| | | | | | | | | | | |
| **IN- PROCESS INSPECTION & TESTING** | | | | | | | | | | |
| | | | | | | | | | | |
| **1** | **Batching and Mixing** | Visual | Batching Plant | Max.Permissible variation:-<br>Water - 1% Cement - 2%<br>Flyash-2% Admixture -3%<br>Sand -+/- 2% CA- MSA<br>10,20,40- 2% 75,150- 3%<br>, For RCC water +/- 5 lit. and S/A ratio +/- 2% | IS:456-2000 , tech specification vol.ii | per pour | every batch | In house | Batching plant printout file | QC incharge |
| | **Ve-be time** | As per ASTM | Ve-be Machine | ve-be sec- 25 +/- 10 sec. | MD& A / Tech Spect. Vol-II | Per Batch | Per Batch | In house | Ve-be time sheet | QC incharge |
| | **Temperature of Concrete.** | As per ASTM | Pocket thermometer. | < 28 Deg. Centigrade. | Tech. Spect. Vol-II | Per Batch | Per Batch | In house | Temp. record file. | QC incharge |
| | **Ve- Be Density** | As per ASTM | Ve-be Machine | > 97.5% of TAFD | Tech. Spect. Vol-I I and MD&A | Per Batch | Per Batch | In house | Ve-be time sheet | QC incharge |

## Table A1-2D

## Typical testing for medium size RCC dam

| S.No | Activity | Inspection / Test method | Instrument used | Acceptance Criteria | Ref. Standard | Sampling plan | Frequency | Testing Agency | Quality record | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| **2** | **Coarse Aggregates** | | | | | | | | | |
| a | Gradation | sieve analysis | IS: sieves | As per T.No.4 IS:383-1970 | IS:383-1970 | Random | weekly | In house | Coarse aggregates testing file | QC incharge |
| b | Moisture content | Drying / weighing as per IS:2386 part-III | weight balance , oven heater or By Aquameter | | IS:2386-1983 | Random | Daily/At the time of Pouring | In house | Coarse aggregates testing file | QC incharge |
| c | Specific gravity & water absorption | IS:2386 Part-III | Density Basket ,Balance, oven | | IS:383-1970<br>IS:2386 | Random | Every dispatch forthnightly | In-house | Coarse aggregates testing file | QC incharge |
| d | Impact Test | As per IS:383 | Impact Test Machine | <45% by wt of aggregates | IS:383-1970 | Random | Every change of source/ Once in a Month | In-house | Coarse aggregates testing file | QC incharge |
| e | Crushing test | As per IS:383 | Comp. Testing machine | <45% by wt of aggregates | IS:383-1970 | Random | Every change of source/ Once in a Month | In-house | Coarse aggregates testing file | QC incharge |
| f | Abrassion test | As per IS:383 | Los Angles machine | < 45% by wt of aggregates | IS:383-1971 | Random | Every change of source/ Once in a Month | In-house | Coarse aggregates testing file | QC incharge |
| g | 75 mic wash | As per IS:383 | IS:sieves | < 15 % | IS:383-1972 | Random | Once in a month | In-house | Coarse aggregates testing file | QC incharge |
| I | Flakiness and Elongation Index. | As per IS-2386 | IS-sieves and metal gauges. | < 25% for RCC. | IS-2386 Part-I | Random | Every change of source/ Once in a Month | In-house | Coarse aggregates testing file | QC incharge |
| **3** | **Sand** | | | | | | | | | |
| a | Gradation | sieve analysis | IS: sieves | as per IS:2386 | IS:2386-1983 | Random | weekly | In house | Sand testing file | QC incharge |
| b | Moisture content | Drying/ weighing | weight balance , oven heater or By Aquameter | | IS:2386-1983 | Random | Per shift | In house | Sand testing file | QC incharge |
| c | 75 mic wash | As per IS:384 | IS:sieves | < 15 % | IS:383-1972 | Random | Once in a month | In-house | Sand testing file | QC incharge |
| d | Specific gravity & water absorption | IS:2386-1963 Part-III | Pycnometer | -- | IS:2386 part iii | Random | Weekly | In- House | Sand testing file | QC incharge |
| | | | | | | | | | | |
| **4** | **RCC and Concrete Placement** | | | | | | | | | |
| a | Wet density of RCC/GEVR | By radioactivity test | Nuclear Density quage | Not less than 95% of TAFD | Tech. Sp.Vol.2 | Random | Per 100 M3 | In- House | Density report | QC incharge |
| b | Dry density of RCC | By radioactivity test | Nuclear Density quage | Not less than 95% of TAFD | Tech. Sp.Vol.2 | Random | Per 100 M3 | In- House | Density report | QC incharge |
| c | Moisture content | By radioactivity test | Nuclear Density quage | 2.5% of optimum designed water content | Tech. Sp.Vol.2 | Random | Per 100 M3 | In- House | Density report | QC incharge |
| d | RCC placement Temperature | By Measurement | Immerssion thermometer | It must be between 7 to 28 C | Tech. Sp.Vol.2 | Random | Per 100 M3 | In- House | Temperature report | QC incharge |
| **5** | **Inspection Check lists** | | | | | | | | | |

# Table A1-2E

## Typical testing for medium size RCC dam

| S.No | Activity | Inspection / Test method | Instrument used | Acceptance Criteria | Ref. Standard | Sampling plan | Frequency | Testing Agency | Quality record | Responsibility |
|---|---|---|---|---|---|---|---|---|---|---|
| **FINAL INSPECTION AND TESTING** | | | | | | | | | | |
| | | | | | | | | | | |
| **1** | **Concrete / RCC** | | | | | | | | | |
| a | Compressive strength of cyclinders | Compressive strength test | Three dial guage m/c | | | | | | | |
| | M-10 | | | 10 N/mm2 after 28 days | IS:456-2000 | Each shift | 15 m3 | In house | Cube casting & testing register | QC Incharge |
| | M-15 | | | 15 N/mm2 after 28 days | | | | | | |
| | M-20 | | | 20 N/mm2 after 28 days | | | | | | |
| | M-25 | | | 25 N/mm2 after 28 days | | | | | | |
| | RCC | | | 15 N/mm2 after 180 days | Tech.Sp.-vol.2 | after 180 Days | Per 2500 M3 | In house | Cylinder casting and Testing | QC Incharge |
| b | Water permiability Test | permiability test by apparatus or packer test | Permiability test appartus, compressor & Packers | < 1% atleast | IS:456-2000 / Tech. Sapect. Vol-II | Randomly | Per 1000 M3 | In house and at site | Permiability test repors file | QC Incharge |
| c | Modulus of Elasticity | Modulus of elasticity test | Elasticity apparatus | | MD&A | Random | Per 1000 M3 | In house | Modulus of elasticity of RCC file | QC Incharge |
| d | Split Test | Split method | CTM and Steel Plates | | MD&A | Random | Per 1000 M4 | In house | Split test file | QC Incharge |
| **e** | **Core samples** | | | | | | | | | |
| | Comp.Strength | Compressive strength test | Three dial guage m/c | 15 N/mm2 | Tech.Sp.-vol.2 | after 180 Days | Per 2500 M3 | In house | Cylinder casting and Testing | QC Incharge |
| | Permeability test | permiability test by apparatus or packer test | Permiability test appartus, compressor & Packers | < 1% atleast | IS:456-2000 | Randomly | Per 1000 M3 | In house and at site | Permiability test repors file | QC Incharge |
| | Density | Water displacement method. | Bucket and measuring Jar | > 2400 Kg/Cu.M. | MD&A | Randomly | Per 1000 M3 | In house and at site | Core log file | QC Incharge |

Table A1-3
Typical testing standards for a large RCC dam

| | **Description** | **Standard** |
|---|---|---|
| 1 | Fly-ash | ASTM C311 |
| 2 | Portland cement | ASTM C114, 109, 204 & 186 |
| 3 | Aggregates | ASTM D75 |
| 4 | Los Angeles test on aggregate | ASTM C131 |
| 5 | Sampling fresh concrete | ASTM C172 |
| 6 | Concrete uniformity | ASTM C94 |
| 7 | Density (unit weight) and yield | ASTM C1325 |
| 8 | Air content | ASTM C231 |
| 9 | Slump | ASTM C143 |
| 10 | Temperature - Temperature will be determined by placing a thermometer in the concrete at the point of placement. | |
| 11 | Making and curing concrete cube test specimens | BS1881-108 & 111 |
| 12 | Capping cylindrical concrete specimens | ASTM C617 |
| 13 | Compressive strength of concrete cube tests specimens | BS1881 - 116 |
| 14 | Compressive strength of concrete cores | ASTM C42 |
| 15 | VeBe method of measuring concrete consistency | see Appendix A |
| 16 | Compressive strength of cores | ASTM C93/C 39M-03 |
| 17 | Direct Tensile strength of cores | USACE CRD – C – 164 |
| 18 | Tensile strength across joints | USACE CRD – C – 164 |
| 19 | Shear Strength across joints | ASTM D 5607 – 02 |
| 20 | Shear Strength across joints | ASTM C 1042 |
| 21 | Static Modulus of Elasticity and Poisson's Ratio | ASTM C 469 – 02 |
| 22 | Standard Test method for Static Modulus of Elasticity of Concrete in tension | USACE CRD – C – 166 |
| 23 | Creep of concrete in compression | ASTM C512 – 02 |
| 24 | Permeability | ASTM D 4360 – 96 (re-approved 2002) |
| 25 | Density, Absorption and Voids | ASTM C 642 – 97 |
| 26 | Rate of Absorption of Water by Concrete | ASTM C 1585 – 04 |
| 27 | Fundamental, Transverse, Longitudinal and Torsional Resonant Frequencies of Concrete Specimens | ASTM C215 – 02 |

Table A1-4A

Typical testing frequencies for a large RCC dam

| | Type of Sample | Frequency | Location | Tests to be carried out | Test Age (days) |
|---|---|---|---|---|---|
| 1 | Cube | 1 000 $m^3$ | Point of Placing in dam | Compressive Strength | 7, 14, 28, 56, 91, 182, 365, 1000 |
| 2 | Cylinder | 5 000/10 000 $m^3$ | Point of Placing in dam | Tensile Strength | 91, 182, 365, 1000 |
| 3 | Cylinder | 100 000 $m^3$ | Point of Placing in dam | Modulus of Deformation in Compression | 2, 7, 14, 28, 56, 91, 182, 365, 1000 |
| 4 | Cylinder | 100 000 $m^3$ | Point of Placing in dam | Poisson's Ratio | 2, 7, 14, 28, 56, 91, 182, 365, 1000 |
| 5 | Cylinder | 100 000 $m^3$ | Point of Placing in dam | Modulus of Deformation in Tension | 91, 182, 365, 1000 |
| 6 | Cube | 100 000 $m^3$ | Point of Placing in dam | Compressive Strength *To correlate with Modulus of Deformation Results* | 2, 7, 14, 28, 56, 91, 182, 365, 1000 |
| 7 | Bulk | 250 $m^3$ | Batching Plant | Ve Be | Immediate |
| | | 250 $m^3$ | Point of Placing in dam | Ve Be | Immediate |
| | | 250 $m^3$ | Batching Plant | Temperature of the RCC | Immediate |
| | | 250 $m^3$ | At point of placing on dam | Temperature of the RCC | Immediate |
| | | In 2 locations for every 500 $m^2$ | At point of placing on dam | Moisture Content of RCC | Immediate |
| | Nuclear Densitometer | In 2 locations for every 500 $m^2$ | The surface of the new layer on the dam at 150 and 300 mm depth. | In situ unit weight | Immediate |
| 8 | Cores | | From galleries in dam and / downstream face | Compressive Strength | 91, 182, 365, 1000 |
| | Cores | | From galleries in dam and / downstream face | Tensile Strength | 91, 182, 365, 1000 |

Table A1-4B

Typical testing frequencies for a large RCC dam

| | **Type of Sample** | **Frequency** | **Location** | **Tests to be carried out** | **Test Age (days)** |
|---|---|---|---|---|---|
| 9 | Cores | | From galleries in dam and / downstream face | Modulus of Deformation in Compression | 91, 182, 365, 1000 |
| 10 | Cores | | From galleries in dam and / downstream face | Poisson's Ratio | 91, 182, 365, 1000 |
| 11 | Inclined core | | From galleries in dam and / downstream face | Shear strength across joints | 91, 182, 365, 1000 |
| 12 | Cores | | From galleries in dam and / downstream face | Modulus of Deformation in Tension | 91, 182, 365, 1000 |
| 13 | Cores | | From galleries in dam and / downstream face | Creep of Concrete in Compression | 91, 182, 365, 1000 |
| 14 | Cores | | From galleries in dam and / downstream face | Density, Absorption and Voids | 91, 182, 365, 1000 |
| 15 | Cores | | From galleries in dam and / downstream face | Rate of Absorption of Water by Concrete | 91, 182, 365, 1000 |
| 16 | Cored boreholes | | From galleries in dam and / downstream face | Permeability | |

Table A1-5A

Testing standards and frequencies for a conventional mass concrete dam

| No. | Material tested | Test procedure | Test Standard* | Frequency** |
|---|---|---|---|---|
| 1 | Cement | Physical and chemical properties | ASTM C150 | Manufacturer's certificate or pre-qualification[1] |
| 2 | Pozzolan | Physical and chemical properties | ASTM C618 | Manufacturer's certificate or pre-qualification[3] |
| 3 | Admixture | | ASTM C494 | Manufacturer's certificate |
| 4 | Aggregates | Petrography | ASTM C295 | As required |
| 5 | Aggregates | Relative density and absorption | ASTM C127<br>ASTM C128 | Bi-monthly[2] or as required |
| 6 | Aggregates | Flat and elongated particles | BS812 | Bi-monthly[4] or as required |
| 7 | Aggregates | Abrasion | ASTM C131 | Bi-monthly[4] or as required |
| 8 | Aggregates | Gradation | ASTM C117<br>ASTM C136 | Daily for each mix (facing, interior concrete) |
| 9 | Aggregates | Moisture content | ASTM C566<br>ASTM C70 | Daily; samples from batching plant's sand silos |
| 10 | CVC (fresh) | Workability | ASTM C143 | Daily for facing and interior concrete and as required |
| 11 | | Air content | ASTM C231 | |
| 12 | | Unit weight | ASTM C138 | |

* Or other appropriate standard. Dam-specific standards are the Designations in the Bureau of Reclamation's Concrete Manual.

** Frequency varies with (a) type and size of the dam, and (b) with the obtained variability. The given frequencies are therefore time-related and may be transferred to relate to quantities of placed concrete for the particular dam.

1. Certificates should include scatter bands (std. dev.) for test parameters considered important (e.g. C3A, alkalis, fineness, compressive strength etc.).
2. For each borrow area.
3. E.g. periodic sampling of concrete taken from individual blocks or from the batching plant.

## Table A1-5B
## Testing standards and frequencies for a conventional mass concrete dam

| No. | Material tested | Test procedure | Test Standard* | Frequency** |
|---|---|---|---|---|
| 13 | CVC (hardened) | Specific weight | ASTM C642 | Daily as above |
| 14 | | Permeability | Special | Bi-annual for facing concrete |
| 15 | | Freezing & thawing | ASTM C666<br>ASTM C671 | Bi-annual for facing concrete in subzero climates[4] |
| 16 | | Laboratory compressive strength | ASTM C39<br>ASTM C116 | Daily as for Nos. *10 to 12* |
| 17 | | Core compressive strength | ASTM C42 | Selective[5] |
| 18 | | Flexural strength | ASTM C293 | Weekly or as required[6] |
| 19 | | Tensile strength (direct and/or splitting) | Special or ASTM C496 | Monthly of facing concrete |
| 20 | | Elastic modulus | ASTM C469 | Selective |
| 21 | | AAR | ASTM C1260 | As required |

*Or other appropriate standard. Dam-specific standards are the Designations in the Bureau of Reclamation's Concrete Manual.

**Frequency varies with (a) type and size of the dam, and (b) with the obtained variability. The given frequencies are therefore time-related and may be transferred to relate to quantities of placed concrete for the particular dam.

4. Also significant for checking concrete durability in any climatic region, see ASTM C 671.
5. Across the entire dam to compare with laboratory compressive strength of same mix design and age.
6. As a redundant test for tensile strength testing because of easy execution. Use the broken halves of the prisms for compressive strength testing (ASTM C116).

## Table A1-6A
## Testing standards and frequencies for a conventional mass concrete dam

### *Plastic or Hardened Concrete*

| Test | Designation No. |
|---|---|
| Sampling | BS 1881 Part 101 |
| Compressive strength | BS 1881 Part 116 |
| Slump | BS 1881 Part 102 |
| Unit weight | BS 1881 Part 107 |
| Chloride ion content | BS 8110.1, BS 6337.4 |
| Drying shrinkage | BS 1881 Part 109 |

*Aggregates*

| | Standard | Sampling/testing frequency |
|---|---|---|
| Sampling | BS 812 Part 102 | Placements up to 10 $m^3$ - 1 sample<br>10 to 40 $m^3$ - 2 samples<br>40 to 80 $m^3$ - 3 samples<br>For each additional 50 $m^3$<br>one additional sample |
| Particle shape | BS 812 Part 105 | 1 per 2 500 $m^3$ |
| Material finer than 75 mm | BS 812 Part 103 | 1 per 500 $m^3$ |
| Light particles | ASTM C123 | 1 per 500 $m^3$ |
| Friable particles | ASTM C142 | 1 per 500 $m^3$ |
| Organic impurities | ASTM C40 | 1 per 500 $m^3$ |
| Soundness | ASTM C88 | 1 per 2 500 $m^3$ |
| Grading | BS 812 Part 103 | 1 per 500 $m^3$ |
| Los Angeles Abrasion | AS 1141:23 - 1995 | 1 per 500 $m^3$ |
| Particle Density and water absorption | AS 1141:5 - 1974 and<br>AS 1141.6 - 1995 | 1 per 500 $m^3$ |
| Alkali reactivity | ASTM C227, C285 | 1 per 2 500 $m^3$ |

*Cementitious Material*

| Test | Standard | Sampling/testing Frequency |
|---|---|---|
| Moisture content | BS 3892 Part 1 and BS 4550 | One every 300 tonnes of continuous production |
| Loss of ignition | BS 3892.1, BS 4550.2 | One every 300 tonnes of continuous production |
| Fineness | BS 3892 Part 1 and BS 4550 | One every 300 tonnes of continuous production |
| Autoclave expansion | ASTM C311, C151 | One every 300 tonnes of continuous production |
| Specific gravity | ASTM C311, C118 | One every 300 tonnes of continuous production |
| Pozzolanic activity | BS 3892 Part 1 | One every 300 tonnes of continuous production |
| Remaining physical and chemical tests | BS 3892 Part 1 and BS 4550 | 1 per 2 000 t |

# APPENDIXES 2

## EXAMPLE OF OUTLINE SPECIFICATION FOR CONCRETE WORK

**The text below is an example for a dam with some 300 000 m$^3$ of concrete to be placed over a three year period.**

**The various tests and test frequencies can be given in the various clauses to which they apply, or may be consolidated into Clause 7 which deals exclusively with testing.**

### 1.0 SCOPE

Requirements for the manufacture, transportation, placement, finishing, repair and curing of concrete; for the detailing, supply and placing of reinforcement; for formwork; for joints, joint materials, joint treatment and bearing pads; and for all other work associated with cast in place and precast concrete.

### 2.0 REFERENCE STANDARDS

List of reference standards and codes for testing.

### 3.0 SUBMISSIONS BY CONTRACTOR

#### 3.01 Certificates and mill test data

The Contractor to furnish data for listed materials.

#### 3.02 Results of tests performed by the Contractor

The Contractor to provide results of all tests and records as well as proposals for tests and trials.

#### 3.03 Samples

The Contractor to provide samples and technical data.

#### 3.04 Construction plant

The Contractor to provide proposals for aggregate and concrete plant.

### 3.05 Construction details

The Contractor to provide details of joints and lift drawings, formwork, etc.

### 3.06 Concreting records

The Contractor to provide daily returns related to concrete production and weather.

### 3.07 Welding of reinforcement

The Contractor to obtain approval for any welding of reinforcement.

## 4.0 MATERIALS

### 4.01 Cementitious materials

#### 4.01.01 General

Materials are to be used.

#### 4.01.02 Cement

Specification for cement.

#### 4.01.03 Cement supply and storage

Storage requirements.

Certificates.

Testing and test frequencies.

Causes for rejection of cement.

Records to be kept.

#### 4.01.04 Pozzolanic materials/ Mineral admixtures

Material sources, reference to standards and particular requirements.

Storage and testing.

### 4.02 Aggregates

#### 4.02.01 General

Sources of aggregate, use of natural and/or crushed materials.

Requirements for provision of testing laboratory.

General requirements for sampling and testing.

Provision of data on quantities and test data.

Correction of deficiencies.

### 4.02.02 Aggregate quality and grading

*Fine aggregate*

Quality requirements for physical and chemical properties, grading requirements, with reference to test standards and codes.

*Coarse aggregate*

Quality requirements for physical and chemical properties, number of grading bands required, grading requirements, with reference to test standards and codes.

### 4.02.03 Sampling and testing of aggregates

Standards for sampling and testing, sample locations, test frequencies.

### 4.02.04 Storage of aggregates

Separation of aggregate sizes, avoidance of contamination, avoidance of undue breaks and segregation, moisture conditioning and moisture requirements.

### 4.02.05 Aggregates for epoxy concrete and mortar

Sources of aggregate, standards to be met, grading requirements and moisture requirements.

## 4.03 Water

Sources of water.

Quality standards to be met.

## 4.04 Chemical Admixtures

The Contractor to provide admixtures required by the project, manufacturer's data and proposed dosage rates.

Storage requirements.

Sampling and testing standards and frequencies.

Compatibility of admixtures.

Required approvals.

Batching.

## 4.05 Concrete Classes

The concrete and mortar grades required for the Works including required strength, age at test, maximum size of aggregate.

## 4.06 Jointing materials and waterstops

Types of jointing materials and waterstops to be used.

Provision of samples and test data.

Approvals required.
Standards to be used.
Required physical and chemical properties.
Required dimensions.
Methods of manufacture and forming joints and connections at site.
Tests to be performed.

### 4.07 Formwork

Materials to be used.
Ties.

### 4.08 Steel reinforcement

Grades of steel and required standards.
Sampling and test requirements and frequencies.
Provision of manufacturer's and independent agencies' test certificates.

### 4.09 Bitumen emulsion

Compliance with standards.

### 4.10 Accessories

Provision of chairs and spacer blocks.

## 5.0 EQUIPMENT

### 5.01 General

Sufficiency of plant and equipment.

### 5.02 Aggregate production plant

Contractor to provide details of plant prior to delivery to site.
Contractor to provide methods of developing aggregate sources.
Contractor to provide production capacities.
Environmental protection.
Production and quality control.

### 5.03 Batching and mixing plant for concrete

Requirements for batching and mixing plant.
Requirements for re-screening.

Method of batching.

Contractor to provide details of batching and mixing plant for approval prior to ordering plant.

Contractor to provide details of how he will check and control the function of the plant.

Requirement for moisture measurement of fine aggregate.

Batch weight tolerances.

Requirements for computer control and automatic operation.

Minimum mixing times.

Documentation requirements.

Maintenance requirements.

Mixer efficiency testing.

### 5.04 Vehicles for transporting concrete

Types of vehicle which may be used.

### 5.05 Vibrators for concrete compaction

Type and main characteristics of vibrators.

### 5.06 Refrigeration plant

Provision of plant for generating chilled water and ice for concrete temperature control.

Provisions for chilling coarse aggregate.

## 6.0 WORKMANSHIP

### 6.01 Proportioning of concrete

#### 6.01.01 Responsibility of Contractor

The Contractor shall be responsible for developing mix designs
or
The Engineer shall be responsible for developing mix designs.

#### 6.01.02 Mix designs

Contractor to carry out a trial mix programme.

Specification of procedures for trial mix design.

Limitations on w/c ratio, cementitious content.

Limitations on the use of admixtures.

### 6.01.03 Trial mixes

Submittal of trial mix programme for approval (for Contractor mix design).

Start date for test programme.

Method of estimating target strengths.

Allowable failure rates.

Numbers of test specimens, specified method of manufacture, maturities at testing, methods of testing.

Provision of reports.

### 6.01.04 Concrete properties and requirements

Concrete constituents.

Required properties of fresh concrete.

Required properties of hardened concrete.

Combined aggregate grading limits.

Expected ranges of cementitious contents.

Maximum size of aggregate.

Required concrete temperature.

## 6.02 Concrete consistency

Slump requirements.

Causes for rejection.

Limitations on adjustment of water in mix to achieve required workability.

## 6.03 Sampling and testing of concrete

Frequency of sampling and casting of test specimens.

Location and method of sampling.

Method of test specimen production and handling of specimens.

Method of testing.

Provision of record of historical strength development and degree of quality control achieved.

Sampling and testing of suspected sub-standard concrete.

Actions to be taken in the vent of non-conformity.

## 6.04 Preparing for concreting

Checks required for cleaning, fixity of reinforcement and imbeds, security of formwork and its alignment.

Provision of plant and tools required.

Preparation of surfaces.

Permissions to pour.

### 6.05 Embedded pipes and other items

Proper location and fit of items.
Provision of openings and voids.
Security of fixing.
Embedding of services required for construction.

### 6.06 Fixing and cover to reinforcement

Methods and security of fixing.
Checking of placed reinforcement.
Concrete cover to reinforcement.

### 6.07 Welding of reinforcement

If and where welding is permitted.
Establishment of procedures.
Requirements for testing.
Certification of welders.
Approvals.

### 6.08 Design and layout of formwork

Responsibilities of the Contractor.
Requirements for alignment, smoothness, rigidity and grout-tightness.
Chamfers.

### 6.09 Erection of formwork

Requirements for alignment, smoothness, rigidity and grout-tightness.
Cleanliness.
Use of mould oils.
Temporary openings required for construction.
Fixing imbeds and void formers.
Requirement for formwork and casting trials.
Approvals required.

### 6.10 Removal of formwork

Care of removal.
Minimum times for removal.
Special requirements in cold weather.

## 6.11 Transporting concrete

Allowable transit times.

Methods to prevent segregation.

Transport into the placement.

Documentation of transported concrete.

## 6.12 Placing concrete

Contractor to submit concrete placing procedures for approval.

General requirements of placement.

Notices to be given and permissions required.

Provision of pre-placement checklists and inspections.

Time limits on placements.

Maximum layer thicknesses.

Requirements for no segregation.

Merging of layers in a lift.

## 6.13 Lift height and time between placement

Maximum allowable lift heights.

Minimum times between successive lifts.

Minimum times between adjacent pours.

Location of construction joints between beams and columns.

## 6.14 Placing temperature

### 6.14.01 Concrete

General requirements.

Thin and moderate sections.

Heavy sections and mass concrete.

## 6.15 Concreting in hot weather

Standards and codes to be applied.

Definition of hot weather conditions.

Methods of reducing temperature of constituents.

Cooling of concrete.

Cooling measures at the placement.

Night versus daytime placements.

Extended waiting periods between lifts.

### 6.16 Concrete placed in water

General prohibition.
Methods to be employed where allowed.

### 6.17 Compaction

Equipment to be used.
Method of employing equipment.
Compaction requirements.

### 6.18 Attendance of steel fixer and carpenter

### 6.19 Curing of concrete

Contractor to provide proposal for approval.
Methods of curing.
Duration of curing.
Use of curing membranes.
Protection against cold, insolation and drying out.
Curing of repairs.

### 6.20 Joints

#### 6.20.01 Construction joints

Contractor to provide details of construction joints not shown on drawings.
Definition of construction joints.
Alignment of construction joints.
Preparation of joints.

#### 6.20.02 Movement joints

Compliance with drawings.
Securing jointing materials.

### 6.21 Placing of jointing materials

Placing and jointing materials.
Welding waterstops on site.
Use of pre-welded joining pieces.
Fixing waterstops.
Use of bond breakers.
Provision of caulking grooves.

### 6.22 Unformed surfaces class of finish

Specification of classes of finish.

### 6.23 Sloping surfaces

Use of slip-forms and travelling screeds.

### 6.24 Formed surfaces class of finish

Specification of classes of finish.

### 6.25 Dimensional tolerances and surface finish of concrete

Dimensional tolerances for various finishes.

### 6.26 Defects in formed surfaces

Methods of repair of various types of surface defects.

### 6.27 Dry pack mortar

### 6.28 Blinding concrete

### 6.29 Epoxy concrete and mortar

### 6.36 Reinforcement details

Contractor to provide bending schedules.
Standards to be applied.

### 6.37 Bending of reinforcement

Standards and codes to be applied.

### 6.38 Storage of reinforcing bars and fabricated mats

## 7.0 TESTING

Testing requirements, frequencies and standards.

## 8.0 MEASUREMENT AND PAYMENT

# APPENDIXES 3

## REDUCTION OF RISK OF THERMAL CRACKING ITEMS WHICH MAY BE SPECIFIED

### 1. Limiting the heat of hydration

- Limitations on the total cementitious content so as to reduce the heat of hydration, possibly with lower stressed (interior) zones with even less cementitious material. Reducing the cementitious content is the most effective way of limiting concrete temperatures.
- The use of low-heat cements.
- Minimum requirements for the inclusion of pozzolan.
- Maximum size of aggregate (MSA).
- Closely defined grading bands (to minimise voids in the aggregate and thus cement content).

### 2. Limiting thermal movements

- Selection of aggregate with low thermal expansion where there is a choice of aggregate source.
- In addition, there may be a limitation on water content to limit autogenous and drying shrinkage.

### 3. Limitations on block sizes, spacing of contraction joints

- For conventional concrete dams, the allowed block sizes and lift heights will be specified, possibly with reference to the drawings. The lift heights may depend on the location within the dam.
- Lifts height on the foundation or on cold concrete may be reduced.
- For RCC dams the induced contraction joint locations will be specified, possibly with reference to the drawings.

### 4. Limiting the maximum concrete temperature

- Maximum placement temperatures, possibly by zone (cooling requirements are normally more severe in concrete close to the foundation and exposed surfaces and openings for water outlets; there may be two or three zones).
- In cold climates, specifying minimum placement temperatures.

- Preventing environmental heat gain or loss (hot and cold climates respectively) by shading, insulation and curing measures.
- Promoting heat loss.
- Prescribing post-cooling.
- Restricting placements to cooler periods such as nights and cooler months of the year.

## 5. Requirements for internal cooling systems

- Outline specification for the chilled water plant or plants where these are required. Typically more than one plant is required to provided redundancy and continuity of operation in the event of a breakdown.
- Use of naturally cold river water for cooling.
- Mean concrete temperatures required at time of grouting joints in arch dams.
- Allowable rates of temperature drop during cooling.
- Requirements for cooling stages (prevention of thermal shock).
- Characteristics of cooling pipes and supply pipes.
- Testing of cooling pipes and system.
- Chilled water circulation systems and controls.
- Temperatures and rates of flow of cooling water with durations of flows including.
- Temperature monitoring requirements and other requirements for instrumentation and control.
- Methods of estimating cooling requirements in response to changing construction and environmental conditions.
- Requirements to close all galleries, air vents and similar large openings to prevent premature and uncontrolled cooling.
- Additional cooling measures to be taken where a cast block has cooled excessively before being covered by new concrete. If the top surface of such a block would provide restraint to concrete placed on top of it and would increase its tendency to crack.
- As an alternative to the above, artificial heating of the excessively cooled top surface has been specified.

## 6. Curing and protection requirements

- Requirements for moist curing.
- Requirements for shading.

- Provision of insulation of forms and unformed surfaces, particularly lift joints, in cold weather conditions.
- Provision of water misters to lower temperatures and prevent drying out while finishing and curing unformed surfaces, such as spillway floors, and RCC lift surfaces.
- Provision of plastic sheeting, wind breaks and shading to prevent premature drying of unformed surfaces during finishing operations.
- Normally, curing compounds (membranes) will be prohibited from most areas of mass concrete.
- Avoidance of thermal shock when forms are removed by limiting the rate of temperature drop of the concrete surface.
- Avoidance of quick drying at the end of the curing period.

### 7. Other construction procedures

- Avoidance of stress raisers (stress inducers) by inclusion of construction aids, such as temporary box-outs, in the concrete.
- The minimum delay between lifts in conventional concrete dams is commonly set to 72 hours (waiting time). This coincides roughly with the time required to erect formwork and prepare for concreting and it allows some heat to be dissipated before the cast block is covered by new concrete. The waiting time should not extend too much beyond this and preferably not more than 7 days (depending on a number of factors) as the concrete might cool excessively and provide unwanted constraint to the overlying concrete.
- Limitations on height differences between adjacent blocks to obtain even joint openings. Maximum differences may be of the order of 8 to 10 m for adjacent blocks and 12 to 15 m between any blocks.

# APPENDIXES 4

## REDUCTION OF RISK OF THERMAL CRACKING
## PRINCIPAL QUALITY CONTROL ACTIVITIES

### 1. Pre-placement

- Ensure joints are placed as shown on the drawings and that none are omitted.

Where internal cooling is used:

- Ensure that cooling pipes are fixed in their proper location and tested for leaks before, during and after concreting and at the same times check that there are no blockages by measuring the head losses during flow tests.
- Ensure that thermocouples are installed as specified and are functioning.
- Ensure that thermometers and temperature sensors on the cooling water circuits are in place and functioning.
- Check that the installed cooling measures and their planned operation are correct for the prevailing climatic and construction conditions.

### 2. Placement

- Verify concrete placement temperatures.
- Ensure that measures designed to prevent plastic shrinkage are installed and functioning.

### 3. Post-placement

- Verify that all prescribed curing measures are installed and are maintained in operation for the specified periods.
- Ensure continuity in wet curing, surfaces should not be allowed to dry out in the curing period.

Where internal cooling is used:

- Check that prescribed flow rates in the cooling system are maintained.
- Check that the cooling water temperatures are correct for the stage of cooling allowing the prescribed time for initial cooling with warmer cooling water to avoid thermal shock.
- Verify that the prescribed maximum cooling rates are not exceeded (typically 0.58C per day).
- Ensure that the cooling water is circulated from just before concrete is placed until the prescribed concrete temperature has been achieved. (In some

practices cooling is started only after the lift has been poured to avoid any risk of leakage into the fresh concrete.) A final check on the average concrete temperature can be made by stopping the flow in a cooling coil for 3 to 4 days and then measuring the water temperature.

- Frost protection may be needed until the concrete has achieved sufficient strength and after that saturation of the concrete should be avoided. Other measures that may be required to avoid undesired environmental effects are shading to avoid solar heat gain, both during placing and in the curing period, covers to exclude rain and measures to exclude frost which may be insulated or heated formwork and insulating blankets. Temperature gradients can be reduced by insulation, also in hot climates.
- In RCC dams, the method of forming the induced joints will be given on the drawings and in the specification and their location and method of installation has to be verified.

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