PROCEEDINGS

International Symposium on Roller Compacted Concrete Dam

April 21～25 1999

Chengdu, Sichuan Prov.
CHINA

CSHEE

CIGB ICOLD

Volume I

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RCC Dams – Discussions Related to: Design; Construction Planning and Quality Control Intefaces

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—China Institute of Water Resources and Hydropower Research(IWHR)

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Andriolo, Francisco Rodrigues [(1)]

ABSTRACT

For more than a decade, the popularity of RCC dam construction has grown in many countries: RCC is constantly being considered for use in many projects and the height of RCC dams continues to increase. This shows the wide acceptance of RCC methodology in dam construction.

However, there is still some hesitation in designing a new RCC dam higher than the last project. This paper intends to establish a discussion on this line of thought taking into account the design, safety conditions, construction speed, planning and quality control as well as how these activities correlate.

1- INTRODUCTION AND GENERAL ASPECTS

For more than 20 years, RCC has grown in popularity as a dam cosnstruction technique.

In Brazil, the adoption of RCC technique was not only based on cementitious consumption reduction. Since the 60s, concrete class zoning has become very popular (CVC-conventional concrete mass), as well as resistance control at one year age or at least 180 days. These concepts were intended as a way of emphasizing the material's potential. In fact, Brazil's vast territorial extent obliged optimization of materials found near the job site and reduction of the chances of materials being rejected on arrival. On account of this, a series of control procedures evolved and were adopted on the largest concrete dams in the country like Ilha Solteira, Itaipu, Tucurui and others.

Another consequence of the country's vastness is the installation of laboratories in certain strategic locations with the purpose of understanding and pre-qualifying materials, techniques and technologies, as well as labor training and quality control support. The following important events exemplify these actions:

Hydroelectric- CVC Concrete Volume	**Period**	**Event**
Ilha Solteira- 3,680,000m3	1970-1972	Use of CVC Mass with an 84kg/m3 of cementitious consumption (61 cement + 23 Pozzolan). Concretes controlled at 180 days age.
Itumbiara- 2,080,000m3	1975-1980	Concrete class zoning, with age control from 90 to 180 days.
Itaipu- 13,000,000m3	1977-1982	Concrete class zoning, with age control from 180 and 360 days. 90 kg/m3 of cementitious content. Production rate above 750m3/h
Tucurui- 6,000,000m3	1978-1984	Concrete class zoning, with age control at 180 days. Up to 95 kg/m3 of cementitious content. Production rate above 500m3/h

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The construction of Ilha Solteira and Itaipu can be considered milestones in the embracing of a quality control system for CVC concretes. The concrete placing speed possible in Itaipu, at times, more than 750m3/h, was possible because of an adequate control plan.

The control plan adopted at these jobs was analogous to the one shown in Figure 01 and described further on.

This way, when observing bibliographic references that attribute to RCC the advantage of reducing cement content, transferring control ages to older dates like 180 or 360 days, or still, greater construction speed, consider the job's dimension rather than a determined methodology or control routine.

Brazil is now among the five major RCC dam builders, having established particularities based on difficulties, characteristics and the potential of its territorial vastness, as well as economical adversities, technical development rate and professional capacity of labor workmen. It is clear then, ***there is no need to set records***.

On the other hand, RCC construction is based on *simplicity*, and not on the chance of not having to perform certain procedures. **It is a construction technique based on making it simple not making it poorly!**

RCC may be considered [01] for application where no-slump concrete can be transported, placed, and compacted using earth and rock-fill construction equipment. RCC bas developed over the past 20 years in response to the need to provide more economical mass concrete structures. RCC is replacing conventional (CVC) mass concrete as the primary construction material for gravity dams and has become a viable alternative material for structures other than dams. Ideal RCC projects will involve large placement areas, little or no reinforcement, little or no embedded metal work, or other discontinuities such as piles. Application of RCC should be considered when it is economically competitive with other construction methods. It may be used in lieu of conventionally placed concrete in concrete gravity or arch-gravity dams. For many dam projects, the use of RCC may allow a more economical layout and project features such as an over-the-crest spillway as opposed to a side-channel spillway. RCC construction techniques have made RCC gravity dams an economically competitive alternative to conventional concrete and embankment dams.

This reveals that initial acceptance of RCC construction was stronger for the dams of the reservoirs, where loss of water was not the most important consideration. The use of RCC in hydroelectric dams was questioned longer, not being immediately accepted.

Of the dams built around the world, 35-40% are hydroelectric, and the number that have used RCC is growing.

Year	***1985***	***1990***	***1995***	***1998***
Total RCC Dams (approximate)	30	70	185	210
Percentage of Hydroelectric Projects with RCC Dams	25.8	30.0	38.5	39.5

Hydroelectric Power Plant, different from other types of dams, may demand spillways with gates over the dam (to control great discharges, as in the case of Salto Caxias, with a Spillway capacity of 49,000m3/s).

The use of spillways with gates over the dam has chronological implications because of the time needed for construction of the CVC pillars, as well as the necessary hydromechanic assemblies, which creates a certain programming conflict.

Besides the need for pillars, gates and different construction phases, they also demand:

- Careful optimization of access;
- Careful dimensioning of resources (equipment and labor);
- Careful form work optimization;

- Careful planning of construction phases;
- Careful team grouping (because of different activities);
- Careful planning of use of materials for different purposes –CVC and RCC and other applications (cofferdams, landfills, etc...)

No doubt all these difficulties imply in additional costs and schedule problems. There is need for a “**better Engineering**”. The use of RCC in these conditions demands greater thought.

A quality RCC product requires a coordinated effort between the structural designer, the planning engineer, the materials engineer, the materials laboratory, and those responsible for field quality control and quality assurance.

Reference [02]**-** “Concrete Manual”**-** page 258 of its eighth edition (first edition dates 1936) quotes:

“…*The production of uniform and economical concrete is largely dependenton inspection at the batching annd mixing plants. Mix adjustments are made using reslts of gradation and moisture tests of aggregates. Quantities and sequence of each ingredient entering the mixer and mixing time are frequently checked to ensure minimum variations…*

On the other hand, reference [03]**-** the “ACI Manual of Concrete Inspection”**-** in its sixth edition (first edition dates 1941) quotes:

“…Inspection is provided to assure satisfactory work, in accordance with the plans and specifications and with good practice…”

The references stated, more than half a century old, express the need and ascertainment for Quality Control.

So, if the demand is so old and common, why is this concept not innate in all partners and collaborators of a certain enterprise? Why is this common sense so hard to achieve?

2- DESIGN AND CONSTRUCTION CONSIDERATIONS

The design must establish the functionality and feasibility of the project. That is what turns and ***idea*** into ***reality.***

This transformation must safeguard points that are statistically vulnerable and/or extremely relevant.

Knowledge of **all** the properties of the materials involved and possibly used in Construction-Design must be beyond risks.

2.1-RCC Mixes- Requirements

To achieve the highest measure of cost effectiveness and quality product, comparable to what is expected of CVC structures, RCC design should avoid, as much as possible, multiple RCC mixtures, and other construction or forming requirements that tend to interfere with RCC production. Also, the design should not require complex construction procedures.

2.2-Facing Techniques

It may be necessary to provide a durable exposed surface. Cast-in-place CVC concrete or other facing systems may also provide increased watertightness for the upstream face as well as increased resistance to erosion and damage by freezing and thawing. The design for any waterretaining structure constructed using RCC, however, should not put primary reliance on an upstream facing system to protect against seepage. The design for providing watertightness of the structure should rely primarily on the RCC itself; on proper mixture proportions, lift surface treatments, and RCC placement, spreading, and compaction techniques. The CVC concrete used as face also provides a medium for installing contraction joints with waterstops and joint drains.

2.3-Seepage Control and Drainage

One of the most important design considerations for RCC dams is the control of seepage. Excessive seepage is undesirable from the aspect of structural stability, possible long-term adverse effects on durability, adverse appearance of water seepage on the downstream face, and the economic value associated with lost water. Properly proportioned, mixed, placed, and compacted RCC should make as watertight a structure as CVC concrete. In addition to strength requirements, hydraulic structures must be designed to minimize seepage, control uplift pressures and assure long-term durability. The joints between RCC lifts are the major pathways for potential seepage through an RCC dam. Seepage can be controlled by incorporating appropriate design and construction procedures (bedding mortar, contraction joints with waterstops, draining and collecting seepage water). Collection methods include vertical drains with waterstops at the upstream face and vertical drain holes drilled from within the gallery near the upstream and downstream face.

2.4-Galleries

For any major high-head (higher than 12-15m [03]) dam a gallery is necessary to provide a location from which to drill drain or grout holes, to provide drainage for leakage, and to provide access for inspection. Several different gallery designs have been tried in RCC construction [03] . Galleries in dams must be located to provide adequate space for RCC placing and compaction equipment in all areas adjacent to the gallery.

2.5-RCC Permeability and Durability

Conventional cast-in-place or precast air-entrained concrete facing elements of adequate thickness can be used to protect the RCC from damage due to freezing and thawing.

The permeability and watertightness of concrete may be of more concern than the strength, especially with respect to hydraulic structures. The factors affecting the permeability of RCC are essentially the same as those that affect the permeability of CVC concrete.

2.6-Thermal Control and Cracking

Temperature-control measures for RCC typically will be quite similar to those used for CVC. These measures include limiting heat evolution, using insulation, requiring night-time placement, and limiting placement to cool weather. The large RCC surface areas cannot be efficiently protected from high ambient air temperatures, drying winds and absorption of radiant solar energy, thus, experiencing greater early heat gain and more subsequent contraction and cracking. Precooling and/or postcooling techniques may not always be practical for RCC placements.

The extent of thermal cracking in an RCC structure will be affected by the type and degree of temperature control used. The selection of cement and fly ash proportions will significantly affect the heat of hydration and subsequent thermal cracking. To reduce temperature rise, low-heat-of-hydration cement, and the maximum pozzolan replacement of cement consistent with strength requirements, are generally used.

As in the case with most nonreinforced concrete structures, cracks do occur in RCC structures, and, if the structure involved is a dam or other water retention structure, leakage will also occur. Cracking may occur despite measures taken to prevent cracking. The possibility of unplanned cracking should be anticipated in design by providing for drainage conduits and sumps where necessary to remove water from the structure.

2.7-Contraction Joints

Placing vertical transverse contraction joints in dams constructed with RCC and installing waterstops in these joints near the upstream face should be considered for crack control. The number and placement of these formed construction joints can be determined by a thermal study, construction considerations, and by examination of the foundation profile parallel to the dam axis. Joints should be considered where changes occur in the foundation profile (or where the different RCC construction steps can induce different modulus of elasticity, due to different ages) which may cause a concentration of stresses.

If transverse contraction joints are used, standard or new developed waterstops should be installed in an internal zone of CVC at the joint near the upstream face. When RCC is specified designers must carefully consider construction details for such features to minimize their impact on RCC placement and to assure they will perform as intended.

2.8-Mechanical Properties

RCC structures are generally unreinforced and must rely on the concrete is strength to resist compression, shear and tension of applied loads as well as internal stresses caused by non-uniform temperatures (gradients). The compressive strength of concrete is high enough, and seldom a limiting factor in structural design. Unreinforced RCC, as is the case with unreinforced CVC concrete, has limited capacity to resist shear and tensile stresses. Therefore, RCC structures are generally designed so that tensile stresses do not develop under normal operating conditions during the life of the structure.

The RCC construction process results in horizontal lift joints intervals. The strength at untreated lift joint surfaces is generally lower than that of the parent concrete. Therefore, mixture designs, placement procedures and quality control measures to assure maximum bond and strength at the lift joint surfaces are important. Test data from constructed projects indicate that RCC joint strengths are sensitive to:

I. The time interval between the placement of successive lifts;
II. The water and cementitious material content (cement plus pozzolanic material);
III. The joint surface condition and treatment used.

In general, the application of joint treatment (bedding mortar) and rapid placement of successive lifts will produce higher joint strengths. The design values for joint cohesion and tensile strength must be based on a laboratory test program.

2.9-Elastic Properties (Modulus and Creep)

Cracking in RCC structures is normally considered to be caused by thermal behavior, but sometimes they can be induced by creep deformation. Construction speed or deflection in the foundation plan or even RCC steps, can induce differential deformations (settlement) that can cause shear effects, and consequently cracking. This phenomenon is sometimes observed in CVC construction, but is normally controlled by using adequate reinforcement. In RCC construction this phenomenon must be considered in design. The adoption of a transverse contraction joint can be useful.

2.10-Special Surface Treatments For Erosion Protection

Concrete erosion is a major concern and must be considered when designing spillway aprons, stilling basin channels, and other concrete surfaces subject to high velocity flows, or when designing concrete surfaces exposed to the action of abrasive materiais, such as sand gravel, and other waterborne debris. Erosion damage of concrete surfaces can be caused by cavitation or abrasion.

2.11-Anchorage Reinforcement

It becomes necessary at times to embed reinforcing steel in the RCC for the purpose of anchoring various structural features and appendixes. These structural features could be intakes for outlet work, training walls for spillways, parapets, etc. The anchorage of these features to the RCC structure can either be accomplished by installing the rebar during RCC placement, or by drilling and grouting the rebar in place following RCC placement.

3- INVESTIGATION- SELECTION OF MATERIALS – RCC MIXES

3.1- Materials

The required amount of material passing the 0.075mm (No. 200) sieve is greater for RCC than is acceptable for CVC. The larger percentage of fines is used to increase the paste content in the mixture, to fill voids and to contribute to compactability. Additional fines are usually made up of naturally found nonplastic silt and fine sand, or manufactured fines. The use of extra pozzolanic material in lieu of natural fines passing the 0.075mm (No. 200) sieve was successfully used in various projects.

The cementitious materials should conform to the adopted standard quality requirements. The pozzolanic material can replace the fines required, but must be evaluated on a technical and economical basis. Water and admixtures (if used) should conform to the adopted standard quality requirements.

3.2-Workability and Density

The workability of RCC is the property, which determines its capacity to be placed and compacted successfully without harmful segregation. It embodies the concepts of compactability and to some degree moldability and cohesiveness. It is affected by the same factors that affect the workability of CVC conventional concrete, that is, the grading, particle shape, and proportion of the aggregate; the cement content; the presence of chemical and mineral admixtures; and the water content. However, the effect of each factor will not be the same for RCC as for conventional concrete.

3.3-RCC Mix Proportioning

Brazilian mix proportioning practice, using an adequate fines content, destroyed particular classifications proclaimed by some authors like **“High Paste content”, “RCD”, and “Lean”**, by demonstrating similarities in practically every procedure and proportioning routine.

The use of **“High (*or Adequate*) Fines Content”** mixes, shown in the data of the RCC control of Salto Caxias Dam [04]**,** revealed an evolution in the characteristics of compressive strength, practically never seen, and superior to the development of compressive strength in many RCC and CCV mass jobs., as shown in Figures 3.01 and 3.02.

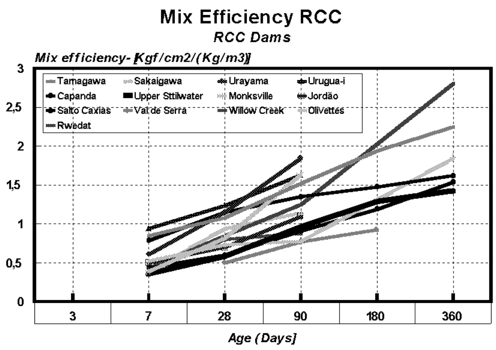


Figure 3.1- Evolution of RCC resistance at Salto Caxias compared to other RCC jobs.

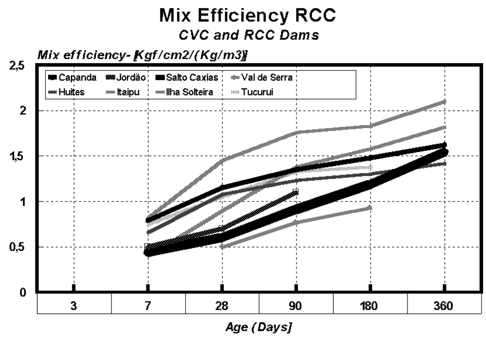


Figure 3.2- Evolution of RCC resistance at Salto Caxias compared to other CVC jobs.

It is important to stress that credit for part of this evolution can be given to the effects of *“moderate”* pozzolanic action of Rock Powder.

The Brazilian proportioning procedure for RCC Dams uses only approximately 4% (in weight)[05] of material external to the job. This has significant advantages in construction cost and material supply logistic.

The need for cement consumption optimization and a predominant and almost systematic use of “Rock Powder” in Brazilian jobs (to this date, around 75% of RCC volume contain powdered rock) have proven favorable, must may have even better results.

The use of plastifier retarder admixtures has proven beneficial both from a technical and economical viewpoint [06].

The maximum aggregate diameter tends to stay between 76 and 50mm and to the present, 85% of the jobs have used a $\mathbf{D_{max}}$ inferior to 100mm

Knowledge of properties and uniformity (as reported in some papers) are arguments in favor of a better cement consumption optimization according to safety and quality conditions oriented by tests and control actions.

4- CONSTRUCTION PLANNING - EQUIPMENT AND TECHNIQUES

4.1- Plant Requirements:-The batching and mixing plant requirements for a project to be built in of RCC are essentially the same as for a project built with conventional concrete. The production, stockpiling, and retrieval of aggregate from the stockpiles are done in the same way and with the same equipment as for conventional concrete. Experience indicates that forced mixers produce faster and more effective mixing and can be used for production of various concrete type.

4.2-RCC Placement Rates:-One of the cost-saving features of RCC is the rapid rate at which it can be placed and consolidated by earthmoving and embankment compaction equipment.

4.3-Transportation:-Properly proportioned RCC can be hauled from the mixer or from the distribution point by a system that does not cause unacceptable segregation

4.4-Placement:-The lift thickness should be determined by the designer and specified in the project specifications. The most important factor governing the placement and performance of RCC is the selection of mixture proportions. Next in importance are the dumping, spreading, and compacting of the RCC.

4.5-Spreading RCC:-The design of dams with lift thicknesses greater than 300mm is based on the realization that constant spreading of the RCC with heavy dozers not only remixes and redistributes the concrete in such a way as to eliminate (and overcome) segregation, but also provides most of the required compaction. This also results in the paste and mortar becoming thoroughly distributed in the mass.

4.6-Compaction:-Each lift is compacted using a vibrating steel-wheel roller. It has been determined from various test sections and actual construction projects that RCC can be adequately compacted using a variety of vibratory compactors. Roller speed has an important effect on compaction [07]**.** Evaluating uniformity throughout the entire depth of the lift has caused control procedures to be adopted as shown in [07].

4.7- Lift Surface Moisture Maintenance:- For roller compression lift surfaces should be moistened and kept continuously damp until the next lift is placed or until the required curing period has ended. This is very important in hot weather conditions.

4.8-Lift Surface Preparation:- Lift surface preparation prior to placement of the overlying RCC lift depends, to some extent, on construction procedures and routines being used. In all cases the surface of the underlying RCC lift surface must be kept moist starting as soon as compaction is performed. Whenever necessary, the lift surface should be cleaned before placement of the next lift. The cleanup should include removal of all loose material, debris, standing or running water, snow, ice, oil, and grease.

4.9-Lift Joint Bedding:-As previously mentioned, RCC structures designed for watertightness require bonding between lifts by applying a bedding mortar over the entire surface area between all lift placements.

4.10-Bedding at Rock Contact:- It involves the spreading of conventional concrete mixtures at the dam foundation abutments

5- QUALITY CONTROL

In Brazil, there is greater concern in achieving uniformity rather than data “numerology”. Therefore, **Inspection** is very important in these construction types.

5.1- The Need for Quality Control

Who does not want assurance that the concrete job in which he is involved will achieve the quality necessary to give good performance and great appearance throughout its intended life? Probably, no one!

The designer wants it; his reputation and professional satisfaction depend on it. The builder wants it for much the same reason, but sometimes there are adverse influences such as time and money problems. The owner wants it; his money is in the project and he has to live with what he gets. Any governmental agency responsible for public welfare and caring of its reputation wants it.

- Why then, if all responsible parties want quality, it is not automatically achieved?
- Why is it necessary to consider what it talkes to get and assure quality?
- Perhaps the answer lies in the inadvertencies, not uncommon in construction activities.
- Perhaps it lies in the loss of pride in craft.
- Perhaps it is inherent in human nature and culture.
- Perhaps, because people are no different today, we need to do something special to insure quality in concrete construction.

Quality control and resulting assurance is no different on concrete construction work. Basically this is inspection and the related testing of materials and concrete. It is however, more than making a few slump (CVC construction) or consistency tests (RCC construction) and cylinders for strength tests. The full scope of duties and responsibilities of the inspection and testing staff are only effective if it includes everyone interacting with them.

5.2- The Need for Inspection

The purpose of inspection is [08] to assure that the requirements and intentions of the contract documents are faithfully accomplished. The term *inspection* as used in concrete construction includes not only visual observation and field measurements, but also laboratory testing and the assembly and evaluation of test data.

One important responsibility for the concrete inspector is the quality of the materials used in the concrete. However, the final materials entering the concrete mixture must be of specified quality. It is difficult and usually impossible to produce specified concrete from nonconforming materials.

On the other hand, a principal ingredient needed for specified concrete construction is good *quality workmanship* in all operations and processes. Manual skills, technical knowledge, motivation, and pride of workmanship -all contribute to good workmanship, which is the real key to quality concrete construction. Workers in concrete jobs may have been exposed to some technical training but seldom adequately. Many workers have pride in their work and do make an attempt to attain satisfactory quality. However, the need to stay within cost limits often requires an emphasis on production rate. Credibility, statistical knowledge, records routines are very effective and efficient where properly applied.

5.2- Quality Plan

An overall Quality Plan or System for a construction can describe in general terms the the objectives and actions with emphasis on:

- The quality objectives to be attained;
- The specific allocation of responsibilities and authority during the different phases of the project;
- The specific procedures, methods and work instructions to be applied;
- Suitable testing, inspection and examination at appropriate stages;
- A method for changes and modifications in a quality plan as the project proceeds;
- Other measures necessary to meet objectives.

The Quality Control System tries to increase the quality and productivity of the works and reduce costs. It must be designed to prevent and eliminate or reduce mistakes during the construction works, and provide repairs, if and when mistakes occur. The design of a structure should be accomplished considering what measures will be required to insure that the required quality is achieved. It is obvious that the design of projects where little quality control is anticipated should be more conservative than the design of a project where a very effective quality control program is anticipated.

While quality control is usually considered to be an activity performed during RCC placement, it is also important that quality control issues be considered during design, planning, and the initial phases of construction of an RCC project.

Procedures need be established, maintained and documented in order to perform, verify and report that the service meets the specified requirements. The reliability, availability and maintainability of the operation need be monitored and reported.

A viable Quality Control System should consider the numerous construction operations basic not only to RCC but also to the CVC, and how they are performed [04]. Preparation and advance planning are the key to success and quality construction.

The Overall Quality Plan must be adjusted to local conditions taking into account the workman labor performance, equipment and technical knowledge, as presented in [04].The control can be based on the following main items:

- A qualified team;
- Adequate and modern technology;
- Adequate equipment and facilities;
- Elimination of mistakes and defects;
- Monitoring of the process;
- Standardizing

All data and information relative to the Quality Control System must be collected in a standardized routine and accurate manner.

RCC placing rates can be extremely high when compared to conventional concrete. With such rapid placement rates or short term construction periods, problems must be evaluated and solutions implemented in a short period of time. Any problems, which delay RCC placing essentially, delays all production. The most common placement delays are usually due to problems caused by:

1. Insufficient materials
2. Foundation preparation and cleanup
3. Joint cleanup
4. Equipment breakdown
5. Weather condition (hot or cold ; wet or dry; rain)

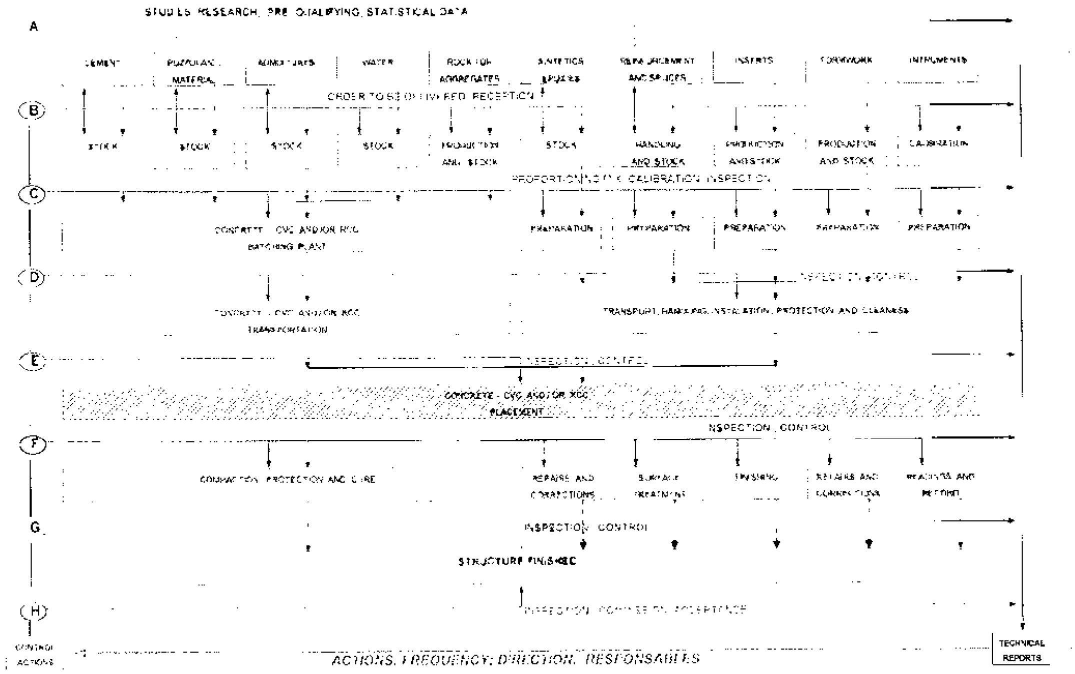


Figure 5.01- Quality Control Actions

It must be assured that all personnel are correctly selected, trained, qualified and motivated so that the results anticipated by the company will be attained and even surpassed. Based on what was described above, it can be suggested that before the works start a “Quality Control Plan” and a “Manual for Quality Control”, as used for Concrete Quality Control during Itaipu Project construction, can be adopted. This "Manual" proposes measures which include the following basic points:

- Be aware of possible problems;
- Anticipate possible corrections;
- Guarantee quality;
- Seek modifications and improvements;
- Be objective, dynamic and compatible with the pace of construction;
- Controls must include materials and concretes (RCC and CVC);

For an overall view of the scheme that can be adopted Figure (5.01) shows a flow chart of actions with the following points:

Action A - Pre-qualification and knowledge -This corresponds to the stage of initial studies, knowledge and selection of materials and suppliers.

Action B – Information on handling.

Action C - Control of arrival (delivered) of material - This action seeks to guarantee quality and uniformity of the material and products, based on pre-qualification data. These tests are proven by certificates, and will be performed by each supplier.

Action D - Control during production - This action is to evaluate the points or procedures that could be vulnerable during production.

Action E - Control of application- This point consists of disciplinary actions during production.

Action F - Inspection during execution- This action will have the function of evaluating the best procedures for executing the works.

Action G - Structure commissioning- This will have the function of formal commissioning of each stage of structures or services.

In addition to inspection activities, a comprehensive RCC quality control program should monitor the aggregate properties, RCC mixture proportions, fresh concrete properties, hardened concrete properties, and in-place compaction. An example of possible tests and test frequencies are given in [09], that was successfully adopted during Capanda RCC Dam construction in Angola. The frequency and extent of testing should be adjusted according to the size of the project, the sensitivity of the design to variations in quality, and the rate of RCC production.

Quality control of the material and concrete used for the Capanda Project, was the Constructor's responsibility. To perform these activities, a "Quality Control Plan" was devised, in order to comply with design and specifications requirements. Logistic conditions for construction of the development were also considered such as, procurement of basic materials, distance from site to production centers, quantity and quality of labor available, schedules, and assurance of quality parameters compatible with the magnitude of the works.

The "goal" of quality control is to identify problems before they occur or sufficiently early in the process so they can be corrected. Monitoring and reacting to the trend in performance is preferable to reacting to specific test results. The trend, identified by a series of tests, is more important than data provided by a single test. By continuously tracking trends it is possible to identify detrimental changes in material performance and initiate corrective actions. Further, it is possible to modify the frequency of testing based on trend performance.

Tests must be performed rapidly. The rapid placing rates and typical 20 or 24 hour per day construction timetables require careful attention and interaction between Quality Control testing, inspection personnel, and production personnel. Fresh RCC properties may vary with daily, weekly, or monthly fluctuations in ambient weather conditions. This, in turn, affects water requirements, compaction characteristics during construction, and the quality of the concrete. Normally, construction activities continue throughout a variety of warm, cold, wet or dry ambient conditions. Quality Control System personnel should assure that continuous adjustments in moisture and, if appropriate, other mixture proportions are made to adapt to these conditions.

Even more than in CVC, the use of compressive strengths test on concrete specimens as a method of control in RCC construction has a major disadvantage in the time required obtaining results. Because of the rapid rate of placement in RCC construction, and the fact that layers of material can be covered with new lifts within hours, test cylinders serve as record data for quality assurance and are not an effective method of day-to-day quality control.

Emphasis on thorough control of materials (gradation, cementitious content, and moisture content) and conditions during placement is essential to proper RCC. An advantage of RCC and the above approach is that unacceptable material is identified early and can be removed at relatively low cost

It is important that qualified personnel be in close contact with the mixing plant at all times to maintain water contents at the optimum level for compaction. The control measures that should be instituted in RCC construction are essentially material dependent.

5.3 – Materials

What inspection and testing then is necessary to provide the quality desired?

This may be divided into material-acceptance testing, concrete production inspection and testing, and inspection of concrete placement and other aspects of construction. Together with these go sufficient record keeping showing what was done and what was obtained. The extent to which each is carried out may vary somewhat in accordance with the size and importance of the job, but always bearing in mind that each is an element in getting quality, regardless of size of job.

Concrete materials other than aggregates can be accepted on certification of the producer but it should be required that these certifications be accompanied by a copy of his test results showing that the cement, pozzolanic materials, or admixture does in fact meet specification requirements. Random samples of delivered materials can be taken, possibly at one month intervals more or less as experience may indicate advisable, and tested for conformance with certification tests.

Cement can be accepted on manufacturer certification, or the suppliers may be required to be “pre-qualified” (see **Action A -** Figure 5.01). In the same way, admixtures can be accepted on manufactures certification, or the suppliers may be required to be “pre-qualified”, also (see **Action A -** Figure 5-01).

The quality and grading of aggregates significantly affect fresh and hardened properties of RCC. The grading of both fine and coarse aggregates affect workability, and the ability to effectively compact or consolidate RCC. In addition to standard gradation analyses, high fine mixtures also require testing for limits of liquid and plastic index. The aggregate source, whether a new on-site source or a commercial off-site source, should be inspected and approved in advance (see **Action A -** Figure 5-01)). An increase or decrease in moisture of only a few tenths of one per cent can change the compacting characteristics of RCC. This is mostly affected if large amount of fines is used [04]. Overly wet stockpiles limit the available water, which may be batched as ice if cooling is required (not usual).

If a PVC membrane is used as an impervious element for the upstream face, control can be performed through factory samples taken before the membrane is sent to site. Similarly, the Quality Control Plan for waterstops can determine control of factory samples.

5.4- Proportioning and Mixing

As in conventional concrete, equipment used for volumetrically proportioning or weight batching of RCC must be carefully calibrated to meet project requirements. This calibration must be maintained throughout the construction period. Experience has shown that the appearance of freshly mixed RCC alone does not provide an adequate indication of the thoroughness with which the material has been mixed. A mixture with homogeneous appearance may not have cement well distributed. A RCC mixture with virtually no cement may handle and appear the same as a lean mixture with cement. Mixer efficiency tests are needed to establish initial minimum mixing times (or retention times for continuous mixers) and maximum mixer loading. Periodic verification of the mixing time should be made during construction by additional tests.

Evaluating RCC mixture proportions has two main aspects:

- First, establishing that materials are entering the mixer with the desired proportions.
- Second, to evaluate the workability of the RCC and the uniformity (or variability) of the mixture proportions after it leaves the mixer or after it has been placed.

5.5- Calibration

5.5.1-Batch-type Plant

Modern batch-type mixers are relatively uncomplicated to calibrate and operate. The primary concerns with RCC are matching aggregate feed rates and storage capacities to high production rates, finding the best batching sequence for each mixture, and getting all materials uniformly blended with a reasonable mix time. The combined charging, mixing, discharge, and return time determines the maximum production rate. Mixture proportions are input from manual or computer controls and are typically recorded by load cells.

5.5.2-Continuous mixing Plant

Continuous mix plants ate relatively easy to calibrate and operate. Mixture proportions are converted to a continuous feed rate in tons/hr (kg/hr). Materials used for calibration tests are accumulated over a fixed period of time rather than being measured individually for a separate batch. As with batch type plants, materials may be individually fed into mixer from separate bins or they may be accumulated on a common final feed belt. This is determined by whether the mixer has, for example, one belt for all aggregate bins or multiple belts with one for each bin. Calibration with just one belt operating may not be the same as when the plant is in full operation with all feed belts operating. Load cells or weigh-bridges to provide weight controls rather than volumetric control, and computer print-outs have been used on some RCC projects but have not been necessary on other projects. Also, as with batch type plants, the mixer should be calibrated at the minimum, average, and maximum production rates expected.

DAM SITE	BATCHER TYPE	THEORETICAL CEMENTITIOUS MIX CONTENT Kg/m3	CONTROLS										
			CEMENT CONTENT			COMPRESSIVE STRENGTH - STATISTICAL DATA							
			AVERAGE Kg/m3	COEFFICIENT OF VARIATION (%)	DEVIATION FROM NOMINAL VALUE (Kg/m3)	AVERAGED VALUES - Kgf/cm2				COEFFICIENT OF VARIATION - %			
						3 DAYS	7 DAYS	28 DAYS	90 DAYS	3 DAYS	7 DAYS	28 DAYS	90 DAYS
SAGO NOVA CLINCA *BRAZIL*	VOLUMETRIC	75	53.4		(-) 21.6		26	29	42				16
	CONTINUOUS	70	50,4		(-) 19 6		26	29	34				18
SERRA DA MESA COFFERDAMS - BRAZIL	VOLUMETRIC CONTINUOUS	60 + 140	188	23,5	(-) 12	76	142	265		31	24	17	
CARAIBAS *BRAZIL*	VOLUMETRIC CONTINUOUS	66	78,4	16	12,4		24	37	36		45 8	54.1	61.1
JORDÃO	GRAVIMETRIC	85	88	12	3		42	54	77		23 6	23 3	16,7
		75	72	13.3	(-) 3		38	55	77		20	15 8	20.3
BRAZIL	CONTINUOUS	70	72	6.3	2		31	41	55		26 6	27 8	18.7
SALTO CAXIAS	GRAVIMETRIC	166	164	5.3	(-) 2		92	119	160		21.2	16 5	18 8
BRAZIL	CONTINUOUS	100	104	4.7	4		36	50	82		19.3	16 0	16 3
URUGUA	GRAVIMETRIC	60	61 5	5,2	1.5		56 5	74	98		16	12	10
ARGENTINA	CONTINUOUS	90	91 1	6.8	1 1		75	96	121		12	10	12
VAL DE SERRA - *BRAZIL*	GRAVIMETRIC CONTINUOUS	90	91 5	4.1	1 5			45	69			24.4	17 4
CAPANDA	GRAVIMETRIC	80	77.6	6 3	(-) 2.4	41	62	86	100	19 9	19 1	17.2	15.9
	BATCHER	70	68,4	5 6	(-) 1.6	38	54	78	93	25	18 8	13.1	9.3
ANGOLA	GRAVIMETRIC	80	82	10.3	2	42	67	93	115				14.9
	CONTINUOUS	70	70.2	16.2	0,2	40	54	78	95	27 7	22 9	18.1	14

Figure 5.02- Reconstitution data of RCC

A diversion conveyor belt, or another equivalent system, is recommended to sample RCC at the plant without stopping the production on large projects. This recommendation is for both concrete plant types.

Figure 5.03- Sampler used at CVC and RCC Continuous Plant

Variability tests can be used to establish minimum mixture retention times and the effectiveness of the mixer feed procedure for both batch and continuous type mixers. They also are used to determine the more important issue of how well and uniformly the RCC is mixed at the placement after it has been delivered and spread.

5.6- Quality Control of RCC During Production

Mix design and statistical data on RCC mixes mainly used in the dam construction and their respective control parameters are shown in Figure (5.01).

To check homogeneity of cement proportioning or mixers efficiency, daily tests were made with reconstitution of cement contents in the RCC fresh mix. This correlation was called test calibration standard. Data obtained during control made through this determination are shown in Figure (5.02).

Once concrete proportions and cement content have been selected for the strength required and are being batched uniformly from the same aggregate, the consistency of the RCC is the primary item for inspection and control. A variable consistency is likely to add to variation in concrete strength. Excessive consistency usually decreases strength through increase water-cement ratio or stratification. RCC of insufficient consistency is likely to lead to poor compaction.

The VeBe apparatus used to measure the consistency of no-slump CVC concrete is used to measure the consistency of wetter RCC mixtures. It provides an indication of the workability or ease of consolidating the concrete in place. When it is used for the wetter types of RCC mixtures, typical VeBe times are 10 to 30 seconds.

To check the influence that not applying the overload would have to the test results, the same sample of RCC was tested indicating a smaller dispersion in tests made with overload. Technique achieved with the Capanda [09] RCC did "**NOT"** produce evidence of absolute applicability of this method [07], probably due to the low plasticity of the RCC, because of the cement content adopted and also the different cohesiveness of fine aggregates content. It was shown that extreme remolding-consistency time values do not always correspond to RCC with deficient compaction.

The moisture or water content is important for several reasons:

- to determine the W/C or W/(C+PM) ratio on projects that may use it in design or design specification requirement;
- to assure the optimum or desired moisture content for workability and compaction, and
- as one of the indicators of mixture variability.

Some moisture test methods are:

(a) Chemical tests (ASTM C-1079)
(b) Drying tests (hot-plate, oven, microwave)
(c) DMA- Brazilian
(d) Nuclear tests- mostly useful for compaction control during the RCC placement

Pacelli and al [11] developed a very simple and rapid method of test to determine the water content and unit weight of RCC. Aiming to establish an alternative to usual methods, a procedure for controlling the unit water of RCC and the unit weight of fresh concrete has been developed. Such method, known as " Water Measurer Device - WMD (DMA in Portuguese), allows the prompt control of unit water during the RCC fabrication.

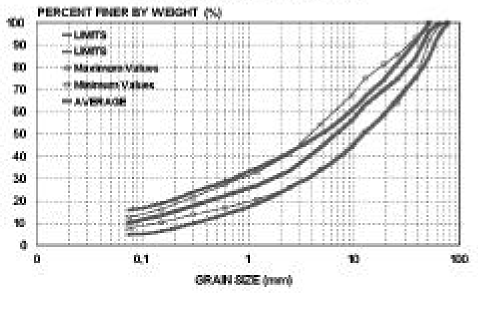
This method has been conceived based on a physical principle, the density of materials compounding concrete. Water being a material with lower density, the more water in a RCC mix, the lower the density.

5.7 – Grain Size Curve Reconstitution of RCC Mix

The RCC mixes used in Brazilian RCC Dams, were proportioned with aggregates having specific gravity of about 2,65-2,95 t/m3, combined so as to obtain the smaller void index. To achieve this, a reference grain size curve was initially adopted for aggregates as follows:

$P = (d/D_{max})^{1/3} \times 100\%$ where

P = Percent Passing:



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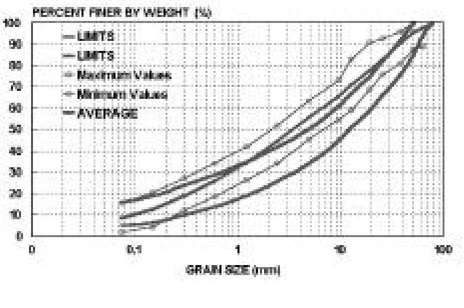


less than 0.3 mm.

Figure 5.04- Granulometric curves for RCC Mixes from reconstitution tests. Note the proximity of average values compared with theoretical value used

The use of batching proportioning isnteady of connetinuous type allows for elimination of this type of control.

5.8- Molding of RCC Cylindrical Test Specimens and Compressive Strength

RCC test cylinders (150mm by 300mm) can be made using procedures suited to the consistency of the mixture, the maximum size aggregate (MSA), and the number of samples to be made before the mixture begins to dry out. Test specimens should be compacted in rigid molds or in removable liners supported during compaction by rigid molds. Wetter consistency mixtures with a VeBe time less than about 30 seconds are well suited to consolidation. The RCC is consolidated in three layers. Other surcharges and modifications have also been used.

The importance of performing concrete strength tests carefully and precisely cannot be overemphasized. In most acceptance confrontations the indicated strength of the concrete is the deciding factor. Usually other questions can be worked out if strength tests are good. If they are not, there is a real problem. So it is important that the tests results are not low due to carelessness and incompetence in sampling, molding, curing, and testing. Aside from dishonesty, there is little that can be done to make a test cylinder stronger than the potential of the original concrete. But there are many things that can reduce its strength. Well trained and supervised people should do this work with care to see primarily that the sample is truly representative and that the cylinder specimens are evenly filled and fully consolidated without voids or rock clusters in any portion; that they are kept wet with visible moisture on the surface at all times and in moderate room temperatures until testing; that capping for testing should be strong, thin, precisely flat, and especially not convex. This need for perfect planes applies also to the two loading surfaces of the testing machine. Convexity or other irregularity of end surfaces has seriously reduced test values and caused needless trouble and concern on too many occasions.

5.9- RCC Quality Control During Placement

RCC methodology has established the convenience of adopting additional controls on site during placement and compaction phases.

Appearance tells much of how well the work was done, but by no means all. And if it is not what it should have been, it is too late to do much about it. Unlike the neatly tabulated results of strength tests in proof of the quality attained, the often hidden good results of construction inspection are not readily documented even though daily shift reports are required. Accordingly, construction inspection will encourage quality by seeing and approving or disapproving, step by step, while action can still be taken if necessary for corrections.

The inspector on the placement operations should watch all details that are related to the overall success of RCC placement operations. The following list indicates some of the items to be checked:

(a) Lift surfaces have been adequately cleaned prior to placement of bedding mortars or RCC;
(b) Bedding mortar (if used) is placed at the required thickness and correct consistency and is adequately spread;

(c) RCC is deposited, spread, and compacted only on fresh bedding mortar (if used) that has not begun to dry or set;
(d) RCC is deposited on lift surfaces in the proper location and spread in the required layer thickness, and the action of the dozers is controlled in a manner to eliminate voids and ensure proper compaction;
(e) RCC as it is deposited and spread is of the required workability as determined by the VeBe tests and by observing spreading and compaction operations;
(f) Compaction of the RCC occurs while RCC is still fresh and has not begun to lose workability;
(g) Lift surfaces are maintained in a moist state at all times;
(h) Internal vibration at interfaces between RCC and CVC concrete is in the right location and done correctly with immersion vibrators in the right number and adequate size and for sufficient duration;
(i) CVC concrete is deposited and consolidated in those areas where it is required such as around waterstops and drains, against abutments, and other locations as shown on the plans;
(j) Installation of contraction joints, if required, is completed prior to compaction by rollers and before RCC has begun to lose workability;
(k) The passes in a specified translation speed for the vibratory roller on each lift of RCC are obtained.
(l) All testing, including VeBe tests, nuclear density tests, aggregate moisture, and grading tests are taken, monitored, and evaluated.

5.10- Compacting Control - Density and Compaction Ratio

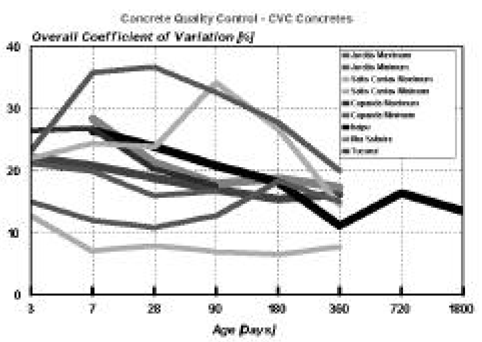
Most vibrating rollers have multiple frequency, amplitude settings and travelling speed. Frequency and amplitude may be displayed on the roller or indicated by “compaction meters” installed in the equipment. Normally, the vibration is interlocked with the motor drive and cannot be checked without the roller moving. Portable tachometers can be placed on the lift surface to test the equipment as it passes by. Amplitude is not easily tested in the field. This is usually a factory calibration test. If there is reason to believe the equipment is not working properly, the equipment manufacturer should be consulted

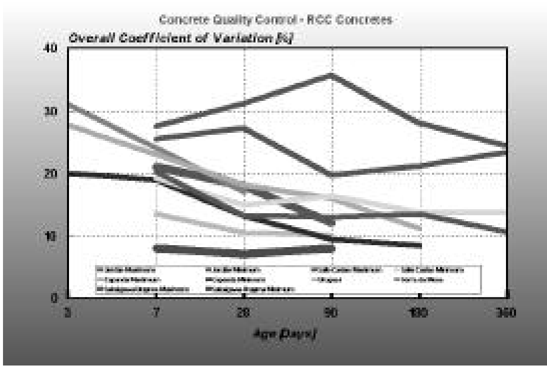
Compaction is affected by the roller travelling speed [07]. This condition must be considered during the RCC layer compaction and the speed should be recorded.

Low densities are the result of various deficiencies including high or low moisture, incomplete rolling, incorrect vibratory amplitude or frequency or speed time delay before rolling, poor gradation or segregation, and non-representative testing.

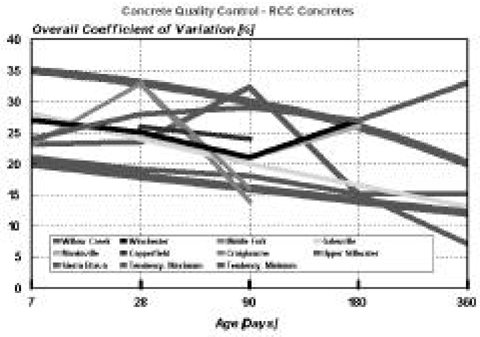
The in-place density of RCC layers can be determined using various procedures. It is however advisable that the procedure used enables not only determination of the compaction value but possibly a supplementary or corrective action of the compacting operation based on the results obtained. Therefore, process swiftness and safety are fundamentally important.

For the RCC used in Salto Caxias Dam, the minimum required compressive strength was (f’ck) of 8 MPa, at age of 180 days, with a deficient quantil of 20% (reduced normal variable "t"=





universe of approximately 25,000 samples representing about 8,800,000 m3. Figure 5.05 also shows comparison values for coefficients of variation, for compressive strength for CVC concrete mainly used in those Projects.



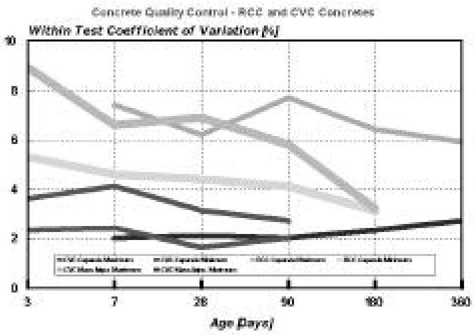


Figure 5.05- Data on Coeffifients of Variation obtained in RCC control compared with values of Coefficients of Variation for Compressive Strength of CVC Mass concrete and RCC in other Projects.

Quality performance of concrete plants, concrete and operators control may be evaluated by the dispersion in the results for compressive strength obtained from the concrete produced by them. In the same way, quality of the strength tests may be evaluated from its own internal dispersion from control. Internal dispersion of the test is evaluated from the difference between the individual values obtained for strength tests in specimens of the same series, broken at the same age.

6- SUMMARY AND RECOMMENDATIONS

The following recommendations can be summarized:

I. Inspection is not an end in itself, but rather a part or subsystem of an overall Quality Assurance system;
II. The overall Quality Assurance system starts with essential and key social parameters that have to be considered and met;
III. The engineer should be involved in order to be able to provide his input and influence the overall decisions;

IV. When the engineer is responsible for the design, he determines what is needed in the drawings and specifications in order to provide the owner with the structure or plant that will perform the service needed at a minimum cost and consistent with the quality required;

V. Quality is more than quality of materials. It should be thought of as the quality of the finished project judged by how well it serves society: physically, functionally, emotionally, environmentally, and economically;

VI. Specifications should be in tune with nature and designed to provide clear requirements that can be met by reasonable men trying to do the work;

VII. Inspection starts during the construction phase or subsystem. There are three basic approaches to conducting the construction operations:
   - Conventional construction where the owner is represented by the engineer and a contractor does the work - still the best approach in most situations;
   - Turnkey type of construction, most useful in very complicated and highly technical and specialized facilities;
   - Construction-manager approach in which the owner delegates the managing of the construction phase to a construction manager, who may differ from the design organization, with a contractor doing the actual work - lack of continuity;

VIII. Quality Control by the various producers or contractor requires inspection as well as inspection for acceptance by whoever represents the owner;

IX. Inspection is, therefore, a key element in the construction phase;

X. Inspection is seeing that good construction in accordance with the plans and specifications is accomplished;

XI. The inspector has to be technically knowledgeable in the field of inspection he is charged with;

XII. All these qualities are expected and proper training and aatitudes are requirements and have to be adequately paid for. It is time that proper training be required and commensurate pay be allowed for this work. Maybe a practical school with a degree in inspection can find a place in our educational systems;

XIII. Communication is the most essential element in inspection. Pre-construction conferences and regular meetings during construction between all parties are essential to get the work done properly and efficiently, to eliminate adversary relationships, and to maintain a team effort;

XIV. The inspector should be proud of his work and be a full-fledged member of the engineering team.

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