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Compaction Control During the Construction of Jordão and Salto Caxias Dams

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Compaction Control During the Construction of Jordão and Salto Caxias Dams

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ABSTRACT

Based on RCC compaction control during the construction of the Jordão River Derivation Dam, performance optimization was attempted in the RCC quality control of the Salto Caxias Project in the Brazilian State of Paraná.

Attention centered mainly on visual aspects of the drilled cores, segregation reduction, elastic-mechanic and permeability properties.

Inspection during RCC construction is usually guided by numbers and parameters of design specifications, but rarely makes reference to visual aspects. RCC construction speed, frequently at a nonstop pace, requires twice the attention if good construction practices are to be established.

Segregation aspects at various RCC layer depths and the compaction ratio must be observed and understood. The search for uniformity must be constant.

1- INTRODUCTION

The Rio Jordão Derivation Dam and Salto Caxias Hydroelectric Power Plant, belonging to COPEL- Paraná Power Company, were built with RCC and have the following characteristics and basic data:

Item - Dam	**Rio Jordão Derivation**	**Salto Caxias**
River	Jordão	Iguaçu
RCC Volume (m3)	576.000	945.600
CCV Volume (m3)	89.000	529.850
Max. Height (m)	95	67
Crest Length (m)	550	1080
Construction Period	02/95 to 03/96	01/96 to 08/98

The following materials were used for the production of RCC and conventional (CVC) concretes:

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1 -COPEL-Companhia Paranaense de Energia- Rua Coronel Dulcídio 800-80420-170-Curitiba-PR.-Brazil- Tel:55-41-322 1212

2 -AiE-Andriolo Ito Engenharia SC Ltda-São Paulo-SP-Brazil-Tel:55-11-260 5613;Fax:55-11-260 7069; e-mail: fandrio@ibm.net; site:www.andriolo.com.br

Characteristic – Dam	Jordão	Salto Caxias
Cement Type	CP IV 32S	CP IV 32S
Cement Supplier	Votoran	Itambé
RCC Cementitious Content (kg/m3)	75 to 105	100
Aggregate Rock Type	Basalt	Basalt
Maximum Size Aggregate (mm)	50	50
Coarse I (4.8-25)mm Content (Kg/m3)	498 to 800	745
Coarse II (25-50)mm Content (Kg/m3)	476 to 534	497
Crushed Sand (≤ 4.8mm) Content (Kg/m3)	1119 to 1473	1143
Fine Material (≤ 0.075mm) Content in Sand (%)	12	18
Water Content (Kg/m3)	76 to 114	143
VeBe Consistency (sec)	20 to 25	15 to 20
Required Strength- fck (MPa) /at Age (days)	8.5/ 180	8.0/ 180

2- RCC COMPACTION

RCC should be understood as a type of ***concrete*** and as a ***new construction methodology***. The main characteristics of the method are given by the transportation, placement and compacting of the concrete.

Because it is concrete of dry consistency -- in order to support the placement and compaction equipment -- the RCC can only be consolidated properly with great compaction effort, an effort mostly resulting from the combination of vibration and pressure, as suggested by Figure 01.

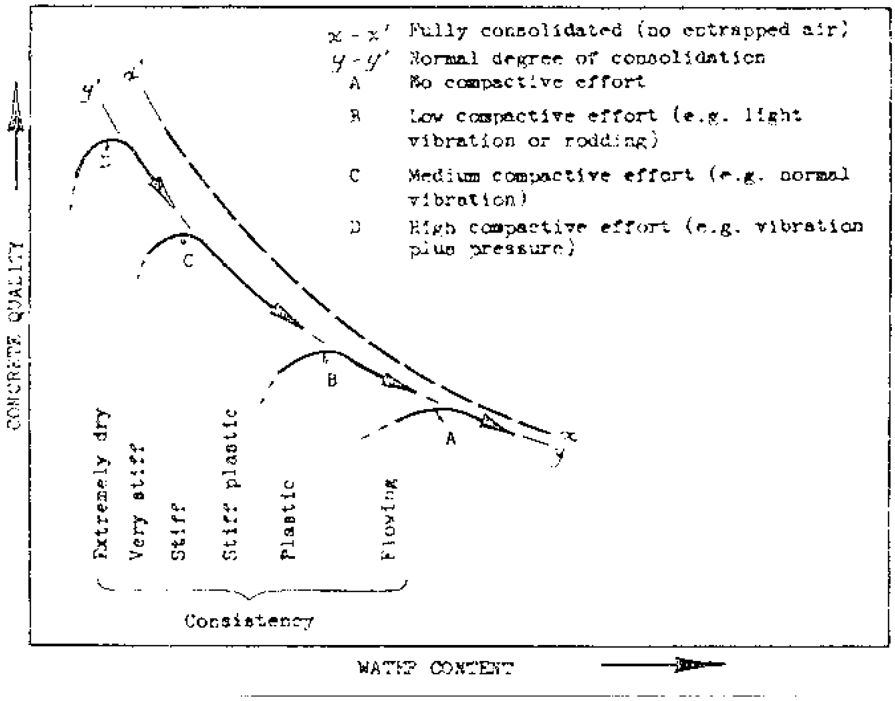


Figure 01- Consistency: Concrete Quality and Water Content [1]

Consistency	**Slump(mm)**	**VeBe (sec)**
Extremely dry	__________	**32 to 18**
Very stiff	__________	**18 to 10**
Stiff	**0 to 25**	**10 to 5**
Stiff plastic	**25 to 75**	**5 to 3**
Plastic	**75 to 125**	**3 to 0**
Highly plastic	**125 to 190**	_________
Flowing	**190 plus**	_________

Consistency classifications (from [1]):

RCC compaction represents an important aspect of the method, once the concrete properties are strongly affected by the quality of this process, in the same way as CVC properties are affected by the vibrating process.

While in CVC consolidation, the effect of vibration is enough to allow for the empty spaces among the aggregates to be filled by mortar, and to eliminate the air bubbles, in RCC, compaction reduces the empty spaces by “overlapping” the aggregates and by filling in the voids with the transmitted vibration. Both mechanisms complement each other, the mix paste (a combination of fine elements and water) functioning as lubricant , and the pressure -- resulting from the weight and vibration – causing circulation of the mortar through the spaces between the aggregates.

Another important particularity of the RCC thickening process, is that the effort and vibration applied at the top of the layer, caused by compaction roller passes, decrease with depth, reaching low values of pressure and acceleration at the bottom of the layer.

3- RCC HOMOGENEITY

3.1- General Considerations

For the construction of RCC dams, the relevant aspects of the project refer to stability, watertightness and durability [7].

All three aspects are affected by the number of construction joints between the compacted layers. Thus, the design, technical specifications and construction quality control must all adequately treat issues related with uniformity and quality of the interfaces between the layers.

In Brazil, and specially in COPEL jobs, construction joints surface treatment have been dealt with using bedding mortar on all the layer’s surface -- as in the Salto Caxias Hydroelectric Power Plant dam – or on the upstream third of the width – as in the Jordão Derivation dam of the Segredo Hydroelectric Power Plant. This is so, regardless of the time lag between the placement of layers.

Similarly, the firm’s professionals involved with RCC have focused on obtaining depth homogeneity of layers. It is possible to obtain optimal performance of the dam body properties and significantly improve the construction joints impermeability, cohesiveness and friction, by improving the quality at the bottom of layers.

It is, thus, essential that RCC compaction properties, proportioning and construction process characteristics that affect compaction quality be adequately investigated and determined.

3.2- Characteristics

During the construction of the Jordão and Salto Caxias dams, cores were drilled from the RCC layers. From those drilled cores, and from data and control elaborated during construction, it is possible to learn about the actions that lead to achievement of the desired quality, and the probable causes for lack of homogeneity in layers.

The observed problems can be classified as:

- Segregation at the bottom of layers;
- Greater porosity at the bottom of layers; and
- Lamination at the top of layers (over-compaction)

3.2.1- Segregation

The accumulation of aggregates at the bottom of layers (Figure 02) is certainly the least desired situation, once it creates horizontal porosity leakage paths in the dam mass body, and reduces those mechanical characteristics of the construction joints and of the concrete related to strength, cohesion and friction, even with linkage mortar between layers.

Figure 02- Accumulation of aggregates in layers (Aggregates not immersed in mortar)

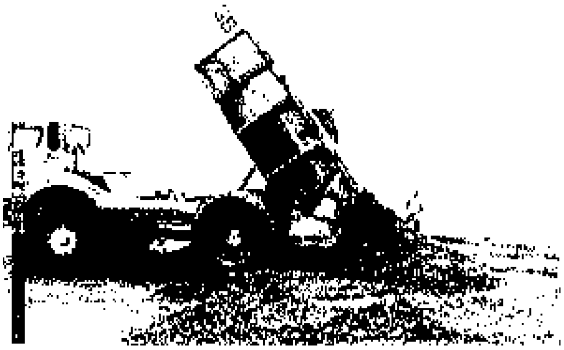


Figure 03 – Discharging of RCC over a spread out layer

If segregation is not generalized, and only found in specific areas, it may have been caused during discharging and spreading of the material, generating clusters of aggregates that, regardless of the compaction energy employed, will not be immersed in mortar (Figure 02). This segregation can worsen with an unbalanced proportioning of the mixture.

To minimize the clustering of aggregates, it is necessary to adjust the grain size and eliminate segregation during production at the RCC batch plant. At the placement front, the segregated aggregate that accumulates at the sides of RCC piles after dumped must be workman handled.

To reduce this problem at the Salto Caxias Hydroelectric Power plant, COPEL used an RCC mix of coarse aggregates, with 60% of coarse I (25-5mm) and the remaining 40% of coarse II

(50-25mm), unlike the proportioning used at the Rio Jordão Derivation dam, where there was a larger accumulation of segregated aggregates.

In addition, other devices were used to reduce segregation during production at the concrete center such as using flexible chutes and hoppers.

At the placement, a common measure adopted at the Salto Caxias plant was to discharge the RCC completely over the spread out layer, such that the aggregate not need be handled to the top of the pile would be remixed during spreading.

3.2.2 Undercompaction

When segregation or porosity of the lower parts of the layers is generalized (Figure 04), it can be attributed to the inadequate adjustment of compaction to the mix and/or chosen execution parameters.

Figure 04 – Drilled cores presenting compaction deficiencies at the bottom of layers (undercompaction)

Figure 05- Core drilled from RCC layer showing overcompaction.

The lack of homogeneity, in these cases, is a consequence of the incapacity of compaction to provide the adequate overlapping of the aggregates and/or the filling of RCC voids by mortar, due to a deficient energy transmission to the bottom.

3.2.3 Overcompaction

The phenomena of overcompaction in RCC can be thought of as a loss in the properties of the concrete caused by excessive compaction.

Possible consequences are the “lamination” of the top portion of the layer, the crack of aggregates at the surface (creating voids in the concrete) or even internally, with no perceived density loss, once what is lost at the top may be gained at the bottom.

Some experiments of direct tensile tests done on cores drilled from the Salto Caxias dam, showed that the breaking point appears under the junction between layers, that is, at the top of the layer.

The above fact illustrates the damages of overcompaction. It points to the need of monitoring the compaction such that this extreme situation is not reached. Still, it was not found often in the cores drilled extracted from the mentioned jobs.

4. ADEQUATING THE RCC COMPACTION PROCESS (RCC/ROLLER SYSTEM)

4.1- General Considerations

Several factors can affect RCC compaction:

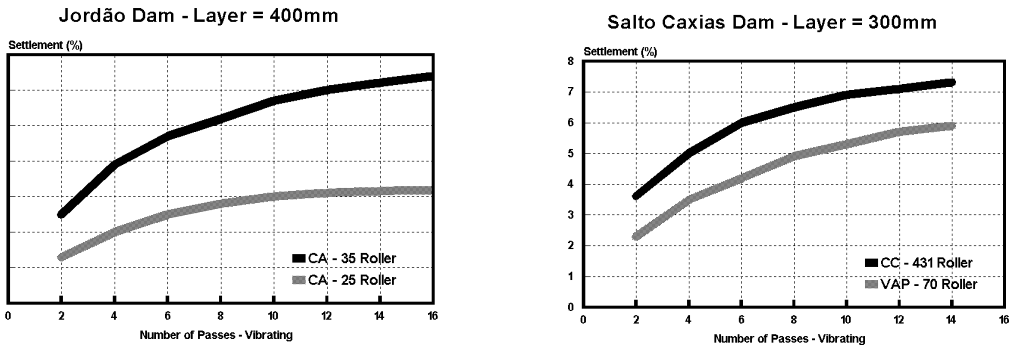
- Workability- consistency of mixtures;
- Proportion, dimension and shape of aggregates;
- Mortar and fines content;
- Layer thickness;
- Time between placement and compaction;
- Aspects pertaining to the compaction equipment (weight, amplitude, frequency, travelling speed)

Weather conditions (wind, temperature, humidity) may cause variations in the construction process and in the mix properties that result in variations in compaction quality. Thus, as each job has its own specific characteristics (site, materials, equipment, costs, etc.), it seems utopian to think of a compaction process good for all situations.

It is, though, possible to establish desirable relations between these factors such as to obtain the best performance of the roller equipment/RCC system.

The previous construction of a field test section are useful in pursueing this goal. When built with the same resources to be used on the job, they allow identifying the adequate conditions relative to the mix proportion, compaction process and equipment.

It is advisable to monitor the setlement of obtained from the top of the layer, as a consequence of the increment in roller passes, in order to evaluate roller compaction capacity, as in Figure 06.



Jordão dam **Salto Caxias dam**

Figure 06 – Evaluation of the number of roller-passes according to the setlement of the top of the layer top (reduction of the voids). Curve examples for different RCC/Roller systems [5;6]

It is possible to evaluate the behavior of the RCC/Roller system used based on the resulting settlement curve (Figure 06). The curve shows the number of passes after which additional passes result in small settlement increments and, consequently, densification. The curve does not indicate the achievement of the desired voids reduction (or density). It only allows establishing the optimal RCC/Roller performance for the given working conditions.

Achievement of a desired RCC quality is aided by matching mix parameters, construction aspects and equipment.

A better interpretation of the results can be obtained with the use of densimeters, and later by drilling cores (Figure 07).

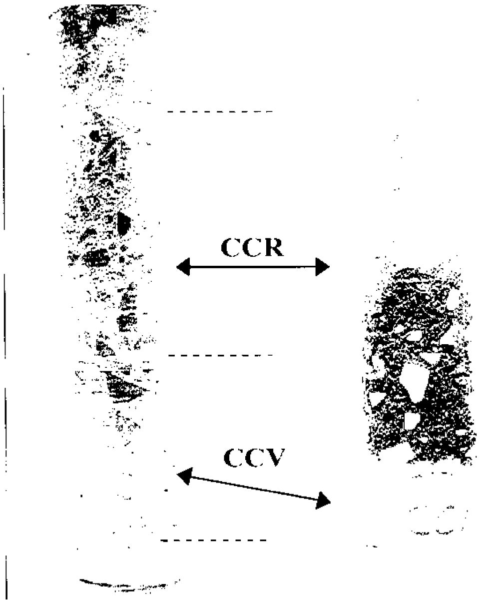


Figure 07- Drilled cores showing homogeneity and porosity relative to CVC

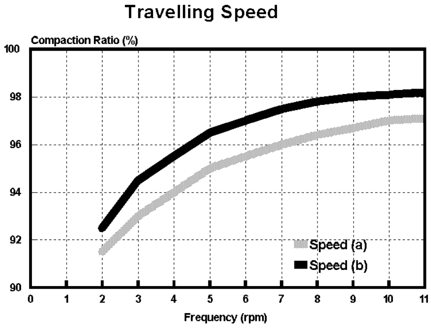


Figure 08 – Effect of speed on soil compaction [4]

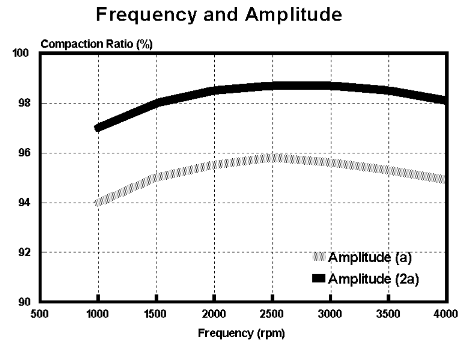
4.2- Actions on the Compaction Equipment

Improvements in compaction performance can be obtained acting upon traveling speed of the compaction rollers and reducing speed.

Still, there’s an operational limit for this reduction. The equipment may not manage to remain stable during compaction, demanding excessive corrections in its direction throughout its move. At the Jordão and Salto Caxias dams, speeds between 2,5km/h and 3,0km/h were generally adequate for the equipment available.

Some rollers allow for adjusting vibration amplitude. This can also be used, respected the operational limits.

Applying more passes of the compaction rollers brings gains in density and, consequently, a reduction of the voids, until a certain point (Figure 06). From that point on, the effective gain is not representative when compared with the energy spent and the loss of productivity of the equipment (higher oil consumption, faster wearing out of the equipment, slower compaction, more equipment, overcompaction, etc.).



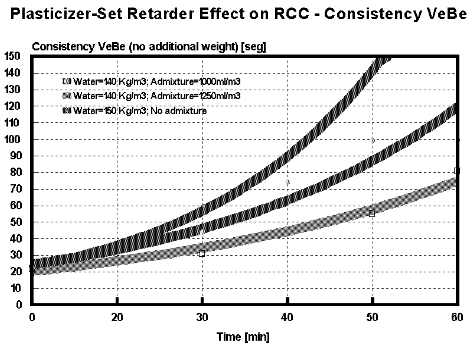


Figure 09 – Effect of the vibration amplitude on soil compaction [4]

Figure 10- Workability loss in time

At Salto Caxias dam, satisfactory results were obtained by applying six dynamic (roundtrip) passes. In the Jordão River Derivation dam, the best results regarding layer density (reduction in voids) were obtained reducing the number of passes from 18 to 10 while reducing speed from around 4,5 km/h to 2,5 km/h.

4.3- Action on the Construction Process and on the Mixes

Other characteristics of the RCC/Roller system may contribute to the inefficiency of compaction in terms of homogeneity, such that action over the compaction equipment parameters alone (speed, amplitude, number of passes, type of roller, etc.) does not result in the desired uniformity.

The Salto Caxias and Jordão dam experiences allow identifying the following characteristics as important:

4.3.1- Layer Thickness.

Too thick a layer reduces the transmitted pressure and acceleration along the layer's depth, inhibiting the aggregate overlapping and liquefying of mortar paste.

For the compaction equipment most commonly used in construction, layers of 300 mm have produced good results. At Salto Caxias dam these layers were more homogeneous than the 400mm layers of the Jordão dam.

4.3.2- Mix Workability.

Workability of mixtures is affected by the shape of particles, by the proportion of fine aggregates, and by the water content of the mix [1]. Workability determination in RCC mixes is usually obtained through modified VeBe experiments.

Workability also falls through time [9] as a consequence of the loss of moisture in the mix as well as the start of setting (Figure 10).

The time lag between RCC placement and the end of its compaction, as well as weather conditions (wind, humidity, temperature) may aggravate reduction in RCC workability.

During the Salto Caxias dam construction summer average temperatures reached 27°C (with highs of 43°C) causing a loss of mix moisture both at the batching plant and at the placement, of up to 7,5 l/m³ [9]. Under these circumstances, moisturizing of the RCC during placement must be constant to reduce the temperature and drying effects.

At the moment of mix production, variations in moisture of aggregates and fine content also cause variations in workability, affecting field compaction performance. Due to the characteristics of the materials, of the site, and weather conditions in Salto Caxias, RCC mixtures with VeBe time (with weight) between 15 and 20 seconds were used, and water content of 7.4% to 7.8%.

These mixtures generally allowed for a VeBe time of approximately 40 seconds (Figure 10) at the moment of compaction [9]. According to results obtained on drilled cores, this seemed adequate for the adopted RCC./Roller system.

4.3.3- Control procedures

A misapplication of the concept of layer compaction ratio may lead to the determination of a minimum compaction ratio for layers, with no attention to the variations in compaction along the layer. This could cause porosity of the lower parts of layers.

The compaction ration would attend to layer control specifications, but the number of passes adopted to obtain the minimum compaction ratio would result in layers with some dense portions and some porous.

This is what happened in the initial phase of the Salto Caxias dam, during the construction of the spillway body. From the moment of density measurement with a nuclear densimeter, the density of intermediate substrata (100mm and 200mm of depth) and that of the layer as a whole (300mm) were used to set a minimum for the density at the bottom of the layer. At the time, measurements indicated an average compaction above 97% with 4 to 5 roller passes, but with 94% compaction at the bottom and 99% compaction at the top.

To obtain a 97% theoretical density at the bottom of the layer it was necessary, in most cases, to obtain a 98.5% average density with 6 dynamic roller passes. This procedure was implemented.

5- LAYER HOMOGENEITY EVALUATION WITH THE USE OF A NUCLEAR DENSIMETER.

Data obtained from drilled cores to determine mix and compaction quality are not enough to guarantee quality throughout construction, and controls during execution of test field or during construction must be established.

The use of densimeters in determining wet density and layer compaction ratio has proved itself a quite efficient uniformity control during the compaction process, specially in large jobs.

Two kinds of nuclear densimeters are used, that with one bar and that with two. The two bar densimeter offers the advantage of measuring density between the source and the detector that are at a same depth, while the densimeter with one bar measures density between source and detector that are at different depths, the source at the bottom of the layer, and the detector at the top (Figure 11).

The two bar densimeter can be used to calculate the density of the layer as a whole by taking the average of the density at different depths. (Figure 11). When using the two bar densimeter, care must be taken to not measure density at the top of an underneath layer, mistakenly taking it to be that of the bottom of an upper layer.

To determine homogeneity, density at varying levels of depth is measured, thus obtaining the density of, say, the upper semi-layer when the bar is put to the middle of the layer, or of any other subdivision as a function of the bars depth.

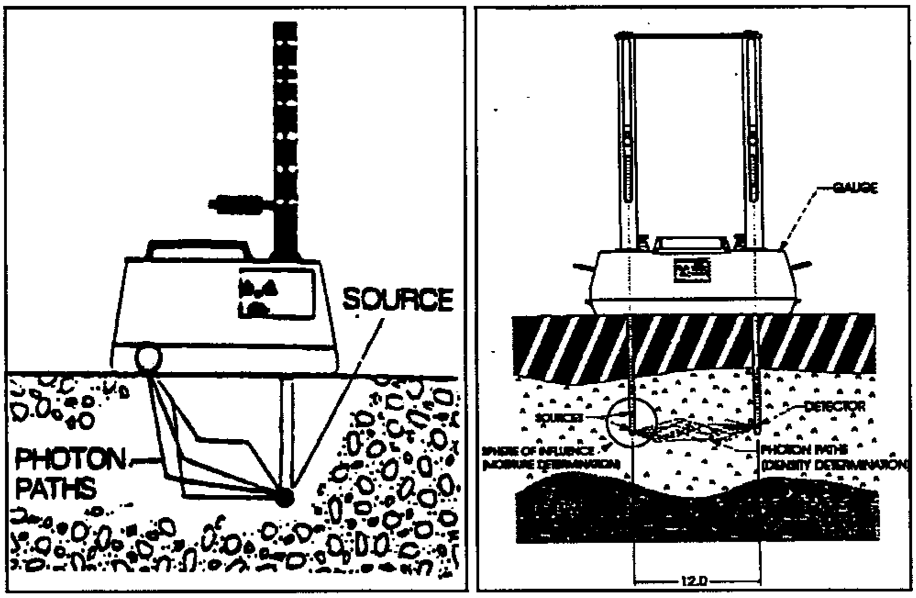


Figure 11- Nuclear densimeters, one and two bars

Regardless of the equipment, proper evaluation of layer homogeneity will be a result of the uniformity in measurements taken at various depths.

During the construction of RCC structures at the Salto Caxias and Jordão dams, quality control done by COPEL used a one bar nuclear densimeter, brand CPN, model MS-3. Density readings were done at 10, 20 and 30cm of depth.

As the densimeter’s bar is limited to measuring up to 30cm of depth, density at the bottom of the 40cm layers of the Jordão River Derivation dam at Segredo Hydrroelectric Power Plant were estimated based on readings done at depths up to 30cm. The following parameters for the Jordão and Caxias jobs were obtained during compaction control based on nuclear densimeter readings of density.

Dam	Density	Number of samples	Coefficient of Variation (%)	RCC Volume (m3) Considered	Volume (m3)/ Sample Ratio
Jordão	2547	346	2.59	230,000	665
Salto Caxias	2600	1882	1.68	945,000	502

As the evaluation of efficiency could be done immediately after reading, by pondering the individual results obtained, measures could be taken in real time, if necessary.

The statistical data obtained from drilled cores can be compaired with the data obtained during the compaction control as obtianed during Salto Caxias dam construction:

Mix	***J.2.e.2***				***J.2.e.6***			
Data	Number of Samples	Density (Kg/m3)	Coefficient of Variation (%)	Compaction Ratio (%)	Number of Samples	Density (Kg/m3)	Coefficient of Variation (%)	Compaction Ratio (%)
Theoretical		**2598**				**2627**		
Densimeter	326	2582	2,12	99,4	1149	2603	1,55	99,1
Cores	145	2580	1,89	99,3	285	2612	1,77	99,4

A more detailed analysis could be obtained using statistical inference, from the gathered data set, for a chosen proportioned mix, a type of compaction equipment, a specific time period, or any other necessary stratification.

From the analysis done, it was possible to determine correction in the methodology, during construction by COPEL, in order to obtain better compaction performance along layers. For example:

- determination of the limit speed for the compaction roller in 2.5 km/h;
- use of RCC mixes with higher water content during periods of high temperatures;
- adjustment of the number of passes in order to obtain layer homogeneity and the adequate work amplitude for each equipment, given the available options.

6. COMMENTS

RCC consolidation through compaction is fundamental for the achievement of the final concrete quality, and to obtain the technical and economic benefits of the construction method.

Obtaining RCC layer homogeneity depends on the proper proportioning of the mixes and the compatibilization of the RCC/roller system, such as to empower the workability-energy relation.

Under this point of view, the RCC mixes proportioning used in the Jordão and Salto Caxias dams that presented best performances were characterized by:

- Adequate proportioning of aggregates such as to obtain the best grain disposition and the reduction of segregation in the batching, transportation and spreading;
- A paste/mortar relation of adequate proportioning of fine aggregates or the filling of the voids of the aggregates; and
- Workability of around 40 seconds of VeBe time (with weight), **at the moment of compaction**.

During the RCC placement, an effort was made to:

- ✓ Eliminate segregation at the unloading and spreading;
- ✓ Reduce variation of layer thickness relative to the chosen measure;
- ✓ Maintain adequate and frequent moisturizing of the front-heads during RCC placement;
- ✓ Guarantee uniformity of compaction throughout the layer, specially in transition areas between rolling strips;
- ✓ Control the number of passes and limit the roller traveling speed during compaction; and
- ✓ Reduce the time lag between the addition of water to the mix and the end of compaction as far as possible (an interval of about 30-45 minutes is recommended for regions with weather similar to that of the mentioned jobs), once RCC workability is one of the factors that most influences compaction quality.

These measures will only produce results if the compaction effort is enough to increase RCC density, specially at the bottom of layers.

Initial research should establish whether the available equipment (amplitude, frequency, weight, traveling speed) is compatible with the adopted width and chosen mix. In general, this investigation depends on the construction of test fill, once the RCC/roller system is not sufficiently simulated by the laboratory methods commonly used.

Finally, controls must be set during mix production and during construction that are capable to verify the achievement of the desired quality, and that can establish immediate corrections, once the productivity imposed by RCC does not allow delays in decision making.

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