CSHEE

CIGB ICOLD

PROCEEDINGS

International Symposium on Roller Compacted Concrete Dam

April 21～25 1999

Chengdu, Sichuan Prov.

CHINA

Volume Ⅰ

RCC Mix Proportioning: High-paste, RCD, Lean or Adequate Fines Content?

Sponsored by: Chinese Society for Hydroelectric Engineering (CSHEE)
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RCC Mix Proportioning: High-paste, RCD, Lean or Adequate Fines Content?

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ABSTRACT

✓What kind of RCC mix is best for dam construction?
✓Low cement content, High-paste content, RCD (Japanese), BaCaRa (French)?
✓How should RCC mixes be proportioned for projects in regions, or even countries that have no pozzolanic material?
✓What is the “real” amount of pozzolanic material that actually “has” Pozzolanic Activity, that is, the ability to react to the elements released during cement hydration?
✓Isn’t a great part of the pozzolanic material acting only as a “filler”?
✓How is this condition of adopting a high content of pozzolanic material considered, while using good pozzolanic cement, to take adequate advantage of chemical components acting as the pozzolanic material already existent in the cement?
✓What is the requirement and interest in the paste/mix ratio?
✓What is the requirement and interest in the sand (fine aggregate)/ total aggregate ratio?
✓What should be considered regarding the “Compaction Ratio”?
✓Why emphasize minor or incidental differences among Rollcrete, RCC, BCR, High-Paste, Lean, RCD?;
✓Aren’t they all **concretes*?***
✓What do they all have in common?
✓And what about costs?

This paper presents an extensive discussion on mix proportioning and arguments for choosing the correct concrete mix.

Proportioning must be achieved with quality and safety so as to obtain workable low-cost mixes with materials **“available”** near the job site. When RCC is conceived as mass concrete, achieving maximum density is very important. On the other hand, economic restraints must be taken into account.

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1- INTRODUCTION

The basic goal of a study on mixture proportioning is to establish a relation between **"available**" materials, so as to achieve concrete that:

- **While still fresh-**
  - Does not segregate, maintaining its uniformity;
  - Is reasonably stable under normal climatic conditions;
  - Can be manipulated for some time, without significant changes to its workability;
- **After hardening -**
  - Has the required properties;
  - Be volumetrically stable (regarding thermal and autogenous volume changes);
  - Be durable;
  - Satisfies established density requirements; and
- **Be low-cost**.

The proportioning study must aim at achieving quality and assurance at a low cost, concentrating therefore on materials **"available"** near the job site. When RCC is established as mass concrete, the need for achieving maximum density is relatively important and must be taken into account. **Economy**, though, must always be considered. Achieving maximum density may originate some discussion. This article intends to establish a debate on the subject.

2- CONCEPTS

RCC is a relatively simple construction technique, but until now, there is no consolidated methodology for mixture proportioning and laboratory testing. Its dry consistency has led many authors to adapt tests, creating at times tendencies or "trademarks".

Some authors or technical groups have frequently emphasized the advantages of adopting a procedure, therefore creating parameters or connections that express a singular significance. This often results in a specific tendency or experience that can not be accepted as a general rule and does not express a global concept.

When establishing RCC mixture proportions, it is common to classify the mix into three basic categories: ***Low, Medium or High-Paste***;

❑***High-Paste Content*** [1 through 5], as in the mix for Upper Stillwater and other dams where a great amount of pozzolanic material was used;

❑***RCD- Roller Compacted Dam Concrete Method*** [6 through 8], used for the Japanese projects with high moisture content RCC, with some high mortar content, resembling a traditional CVC mixture;

❑***Lean RCC*** [9 through 11], originally adopted in the United States, refers to a dry lean RCC with a cementitious (cement + pozzolanic material) content not greater than 100Kg/m3.

In countries like Brazil, with long distances and sometimes poor transportation condition, it is almost impossible to assume only one category of the above. Resources of certain basic materials may, or may not, be available near the job site.

It is well known that the transportation of materials is one of the most important items in the cost composition. Based on this, the use of more expensive materials should always be optimized. This way, it is very important to understand the concepts involved in RCC mixtures proportioning and professionals should look for low-cost complying alternatives.

Mixture proportioning should aim at achieving the highest specific gravity, or the lowest void ratio. Aggregates (according to the grain sizes in which they were produced) should then be combined so as to form a Grain Size curve (combining the individual sizes) closest to the following:

$\mathbf{P = (d/MSA)^{n} \times 100\%}$, where:

P = % passing through sieve “d”;
d = size of the sieve (mm);
MSA = Maximum size of coarse aggregate (mm); and
n= exponent , usually adopted ½ to ¼.

Figure 2.1 illustrates this curve-type for various MSA.

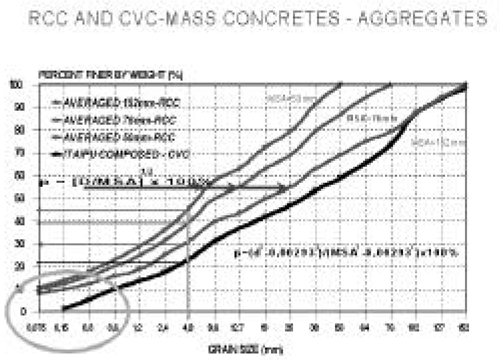

Figure 2.1- Cubic-type curves, adopted in various projects and a combined aggregate curve for conventional mass concrete (CVC)

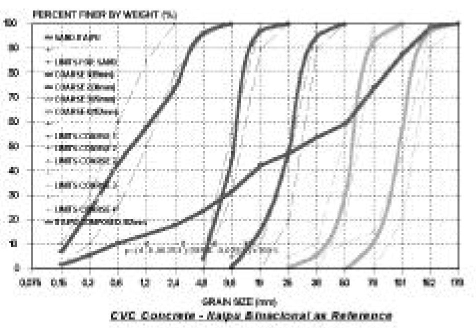

Figure 2.2- Individual curves for each aggregate and curve designed for mass CVC concrete (Itaipu).

The recommended grain size curve, similar to a cubic-type curve, has been advocated and adopted by various authors, entities and projects [11 through 30].

The cubic-type curve is characterized by requiring a certain amount of material smaller than 0.075mm (sieve No. 200). This amount is approximately 8% to 12% of the total amount of aggregates in the mixture, as illustrated in Figure 2.1.

Another characteristic revealed in the cubic-type curve is the reduction of coarse aggregates that usually cause segregation. This can be seen in Figure 2.1, by comparing the individual curves and the combined aggregate curve, commonly used for CVC mass concretes, also shown in Figure 2.2 (and 2.1).

At this point, the fine fraction of the cubic-type curve becomes important because the fines (smaller than 0.075mm), at an 8% to 12% recommended ratio, are helpful in filling the voids and allowing for adequate consistency, mixture cohesiveness and compaction. The use of fines in the RCC mix, based on the cubic-type curve, has shown innumerous advantages not only increasing the mixture’s cohesiveness in its fresh state, but also accounting for benefits in the RCC in its hardened state.

It is possible to fill these voids with fly ash or milled slag, or by using a “filler” produced by the crushing of aggregates, or silt.

The many references to RCC mix proportioning lead to the following “recommendations” summarized in Figure 3.1.

3- DATA AND INFORMATION

RCC mix proportioning references instruct:

“*The in situ density of concrete will depend to a great extent on the relative density of the aggregates to be used. In addition to this, the two most important factors are the void ratio of the fine aggregate and the paste/mortar ratio. The latter factor was introduced in the middle 1970s [1][2]. It is the ratio of the volume of paste (i.e. cementitious content and water plus entrained air, if used) to the volume of mortar (i.e. paste and fine aggregate) [3].”*

In [3] an additional information is worth note:

“ *The densities are plotted against the paste/mortar ratio of concretes where this defined as the ratio of the volume of paste (i.e. cement +* ***FLY ASH OR SLAG*** *{if any} + entrained air {if any} to the volume of mortar (i.e. paste + fine aggregate - say the passing the 5-mm sieve)’* [3] (the part in bold letters is by the authors of this paper).

Reference [6] also recommends:

“When using RCD Method, it is especially important to select a mix design with which compaction of concrete will be made easy on carrying out proportioning tests. Here, concretes were mixed with sand-aggregate ratio varied at several levels while maintaining unit binder content (unit cement-plus-fly ash content) and unit water content constant, and comparison studies were made on measuring the respective vibrating compaction (VC) values.

...... As is clearly shown ... there exists a s/a at which VC value will be a minimum. This s/a is the s/a of concrete at which compaction is most easily accomplished, and is in a range of 32% to 34%.”

Reference [7] establishes:

“The sand-aggregate ratio was selected to be 30% from the results of laboratory tests measuring Vc values varying the sand-aggregate ratio and...”

And from [8] it is possible to observe:

“According to the principles of mix design for RCD concrete, voids in compacted coarse aggregates must be filled up with mortar in compacted fine aggregates must be filled up with paste, but the ***AMOUNT OF PASTE MUST BE RESTRICTED TO A MINIMUM.****” (*the part in bold letters is by the authors of this paper).

Another mix proportioning criterion can be observed in [11]:

"Fine and coarse aggregate should be proportioned to create a well-graded combined aggregate.... ....The addition of material finer than the 0,075mm (No. 200) sieve may be necessary to supplement fine aggregate in order to reduce the volume of voids within the fine aggregate and to produce a more cohesive mixture. This supplemental fine material may consist of fly ash, natural pozzolan, ground granulated blast furnace slag (GGBF slag), or natural fine sand. The use of fly ash, natural pozzolan, or GGBF slag as supplemental fine material may provide added benefits as a result of reduced overall water demand, lower water to cementitious material ratio, and higher ultimate strength."

The (sand)/(total aggregate) ratio usually considered in studies on conventional –CVC- mass concrete varies for each group of aggregates, decreasing proportionally to the increase of Dmax, as illustrated in Figure 2.2 [38 and 39]. The same can be observed for RCC when using the cubic-type curve, as illustrated in Figure 2.1.

Figure 2.1 shows that by comparing the adopted RCC cubic curve to the combined aggregates curve, there is a bigger mortar amount in RCC than in CVC.

When reducing the cement content in lean RCC mixes the corresponding voids must be filled with Fly Ash, slag or, again, by aggregates (or by the "filler" of these aggregates).

According to the references quoted above, the following basic recommendations should be observed so as to achieve maximum density and maximum compaction:

- *paste/mortar ratio should not be lower than 0.35;*
- *Paste must contain Fly-Ash or Slag;*
- *(sand)/(total aggregates) ratio should not be lower than 0.3*.

The quoted reference that establishes a minimum (paste)/(mortar) ratio conflicts with [8] that recommends that **the amount of paste must be restricted to a minimum**.

Figure 3.1 shows details of RCC mix proportioning (or High-Paste or Japanese-RCD, or Lean RCC, and the ***High Fines Content*** Brazilian model) used in many dams and studies.

The facts gathered here show that:

❑***Paste/Mortar ratio:*** Practically all mixes comply with the quoted references. It should be observed, though, that the Japanese-RCD practice attempts to decrease the ratio, as opposed to High-Paste content mixes;

❑***Paste Content***: Standard High-Paste proportioning recommends a paste content of a minimum of 20% of the total RCC volume. All mix designs comply with this parameter except Japanese-RCD mixes; these have a slightly greater water content and their consistency/workability is more related to the water than the paste-mortar. It should be noticed that high fines content mixes are responsible for the highest values according to the examples shown here;

❑***Sand/ Total Aggregate Ratio***: Generally speaking, practically all standard practices comply with this recommendation. Here too the high fines content is the one that presents the greater values;

❑***Compaction Ratio***: All standard practices present values above 95%, the lowest corresponding to High-Paste content mixes;

❑***Mix Efficiency (commpressive strength/cementitious content)***: Results are relatively similar although the Japanese-RCD mixes provide slightly higher values;

❑ ***Tensile Stregth (related to Compressive Strength):*** Practically all values correspond to a same interval;

Parameter-Reference	High Paste	RCD-Japan	Lean	Adequate Fines
Granulometric Curve	Not indicating	CVC	Cubic	Cubic
Cementitious Content (cement + pozzolanic material)	≥ [illegible]50	120-130	≤ 100	The necessary amount for the desired properties
Paste/Mortar Ratio	35 % to 41%	Must be minimum	Not indicating	Not indicating
Paste	Must contain Pozzolanic Material or "Filler"	Must contain Pozzolanic Material	No indication	No indication
Paste Volume (in relation to total RCC volume)	≥ 20%	Must be minimum	No indication	No indication
Sand/ Total Aggregate Ratio		≥ 30 %		
Fines Content	No indication	No indication	8% a 12%	8% a 12%
Compaction Ratio	90% a 98%	No indication	No indication	No indication
Dams used as reference	*Upper Sttilwater; Serra da Mesa;Lake Robertson;Knellport;Woveldans;Castilblanco de los Arroyos; Yantan;Kengkou;Shuikou*	*Shimajigawa; Tamagawa; Nunome; Elk Creek*	*Monksville;Galesville;Arabie;Zaaihoek;Santa Eugenia;*	*Capanda; Urugua-I; Jordão; Salto Caxias;*
Granulometric Curve-Used	***Basic-Exponential***	***No indication***	***Cubic***	***Cubic***
Cementitious content adopted (cement + pozzolanic material)	***120 to 2[illegible]51 kg/m3***	***120 to 130 kg/m3***	***66 to 125 kg/m3***	***60 to 105 kg/m3***
(Paste/Mortar) ratio obtained	***39% to 50%***	***40% to 45%***	***38% to 52%***	***33% to 45%***
Paste content obtained	***17% to 26%***	***18% to 19%***	***19% to 22%***	***20% to 28%***
Sand/ Total Aggregate ratio used	***28% to 37%***	***27% to 34%***	***27% to 40%***	***42% to 53%***
Specific Density (Nominal Value)	***2,35 to 2,50 t/m3***	***2,35 to 2,[illegible]1t/m3***	***2,34 to 2,[illegible]1t/m3***	***2,42 to 2,71t/m3***
Specific Density obtained	***2,34 to 2,49 t/m3***	***2,34 to 2,44t/m3***	***2,28 to 2,[illegible]1t/m3***	***2,41 to 2,[illegible]5t/m3***
Compaction Ratio Obtained	***95,4% to 99,4%***	***98,5% to 99,2%***	***98,7% to 99,8%***	***97,3% to 99,0***
Compressive Strength Efficiency at 28 days age	***0,058 to 0,107 MPa***	***0,08[illegible] to 0,115 MPa***	***0,04[illegible] to 0,167 MPa***	***0,05[illegible] to 0,115 MPa***
à Tração Resistance (Diametral Compression) expressed as % of Compressive Strength	***5% to 19%***	***15% to 20%***	***9% to 19%***	***6% to 19%***
Cohesion (as % of Compressive Strength)- treated joint	***20% to 26%***	***22% 25%***	***Few values***	***22% to 37%***
Friction Angle - treated joint	***57º to 64º***	***49º to 52º***	***46º to 67º***	***50º to 65º***
Permeability (m/s)	***10^{-12} to 10^{-10}***	***10^{-9} to 10^{-8}***	***10^{-9} to 10^{-6}***	***$10^{-1[illegible]}$ to 10^{-9}***
Costs-of Materials external to the job	***5% to 10%***	***5,0% to 5,5%***	***≤ 5%***	***≤ 4%***

Figure 3.1- Comparative Data [1 through 32]

❑***Cohesion***: Practically all values correspond to a same interval;

❑***Friction Angle***: Practically all values correspond to a same interval;

❑***Permeability***: The lowest permeability values refer to High-Paste content mixes followed by high fine content mixes;

❑***Granulometric Curve***: Almost all mixtures follow an exponential Grain Size Curve, very similar to the cubic type, with small adjustments of the edges (coarse and fine);

❑***Cementitious Content***: The range with lower values refer to High Fines content, followed by the Lean type, Japanese-RCD, and the highest values refer to the High-Paste grading;

❑***Adiabatic Temperature Rise***: Practically all values correspond to a same interval as expressed by a Coefficient of Adiabatic Temperature Rise (oC/Cementitious Content-[Kg/m3[),as shown on Figure 3.2

Coefficient of Adiabatic Temperature Rise 100*[°C/(Kg/m³)]-
Cement= 100 Kg/m3; Pozzolanic Material or Fines= 60 Kg/m3

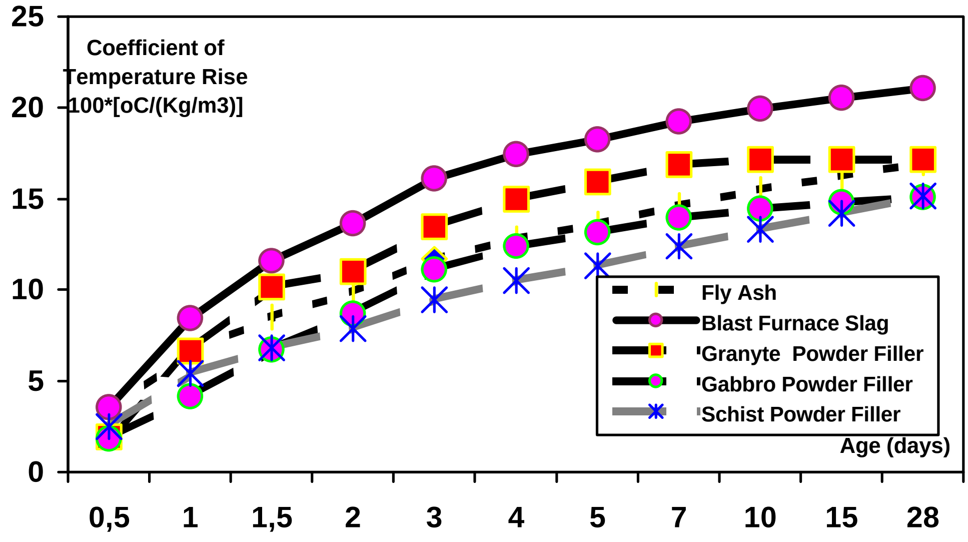

Figure 3.2- Adiabatic temperature rise

The authors would like to stress the following points:

⇒Values for the different RCC mixes are similar;

⇒The lowest permeability values noted in the High-Paste examples are achieved basically by increasing the cemedntitious content of the mixes, which are finer than the “fines” used in the other standard mixtures;

⇒On the other hand, the high cementitious content of the High-Paste misture produces major heat, that may lead the structur into a crack inducing situation, which paradoxically allows for a permeable structure [13];

⇒Also and most importantly, an increase in the binder content reflects on costs and has serious implications in countries or areas with great transportation distances, like Brazil.

When observing the group of information and data reported here, the question may rise:

❖What then are the main differences between mix proportioning standards that may help establish a “tendency” or “trademark”?

The authors of this article strongly affirm: there aren’t any. On the contrary, Brazilian practice, with a high fines content, is more capable of reducing costs with comparable resistance and durability. Mixes with high fines content are those that use less external materials (in weight) (in this case, cementitious materials) so the potential for reducing costs is great.

It can be still observed:

- When using a great amount of Fly Ash, Sl;ag, or other pozzolanic material, how much is really involved in pozzolanic activity and reacting with the hydroxides available in the cement? Or, would a certain amount be acting only as inert filler? At what cost would it be worth transporting that amount of Pozzolanic?
- When using fines produced from crushed material (at the job site) or Silt (from the near region), the question that rises is whether these materials have any benefic additional pozzolanic activity, without additional cost.

Thus the need for a technical and economic balance so as to optimize the use of materials.

4- COMMENTS

As a general rule, the authors of this paper strongly hold the opinion that the material chosen should be that which offers more benefits at a lower cost.

Data reported here shows that:

- The use of fines in RCC is extremely valuable to improve the properties as already stated in other references [11; 13; 16; 17; 24; 25; 26; 31 e 32]
- The fines used do not necessarily have to be fly ash or slag, but may be a by-product of aggregate manufacturing (Rock Flour) [24; 31 e 32] or a Silt [27; 28; 29].
- Considering that compressive strength is not the most important requirement for gravity dams it is convenient and sensible to use a low-cost fine material;
- A low cement content RCC, like the one stated as a high fines content standard mix provide the mass structure with a better thermal performance;
- With low cementitious RCC (Lean and high fines RCC) construction joints should be analyzed and solved according to project requirements and with adequate treatment in order to guarantee the necessary cohesion (since friction practically is unaltered by cement use);
- The permeability coefficient of RCC with high fines content is reduced [13] providing the structure with a greater watertightness without inducing cracks caused by a increase in the cementitious content;
- The compaction ratio, that reflects the Quality Control performance in high fines content mixes, is practically above 97%;

- The data obtained and provided does not justify the need for marking differences in the various RCC (or RCD or Lean or High Paste) mixes, justified only by a need for characterizing a trademark!

5- LAB RESEARCH

5.1. Scope

FURNAS Concrete Laboratory has done research on high fines content RCC using cementitious material formed by cement complemented by the following fines content: fly-ash, active silica and powdered aggregate.

Tests were carried out on fresh and hardened concrete [33 a 36]. Tables 5.1.1 to 5.1.3 present mixes with different fines materials for a cementitious content of 160 kg/m³ and different water contents. The tests are illustrated following:

5.2. Fresh Concrete Tests

The permeability of fresh concrete, determined using the procedure described in [34], presents the values shown in Figure 5.2.1.

Table 5.1.1 - RCC mix with fly-ash – Water Unit Variation

Composition	**F80/80**				**F100/60**				**F120/40**			
Cement	80				100				120			
Fly Ash	80				60				40			
Water	120	130	140	150	120	130	140	150	120	130	140	150
Sand	900				900				900			
Granite	1254	1228	1200	1174	1264	1236	1210	1184	1272	1246	1218	1192

Table 5.1.2 - RCC mix with powdered granite - Water Unit Variation

Composition	**G80/80**			**G100/60**			**G120/40**		
Cement	80			100			120		
Powdered Granite	80			60			40		
Water	130	135	140	130	135	140	130	135	140
Sand	900	1000	1100	900	1000	1100	900	1000	1100
Granite	1304	1290	1278	1306	1294	1280	1308	1296	1282

Table 5.1.3 - RCC mix with active silica - Water Unit Variation

Composition	**S80/20**				**S100/20**			
Cement	80				100			
Silica	20				20			
Water	120	130	135	140	120	130	135	140
Sand	1000				1000			
Granite	1248	1222	1208	1196	1232	1206	1192	1178

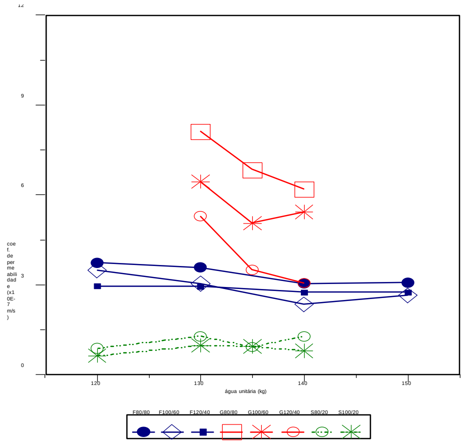

Figure 5.2.1 – Fresh Concrete Permeability

5.3. Tests on hardened Concrete

5.3.1. Compressive Strength

Compressive strength tests at 90 days age are illustrated in Figure 5.3.1.

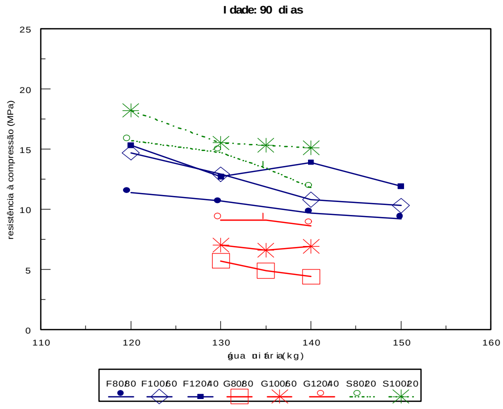

Figure 5.3.1 – Compressive strength

5.3.2. Permeability

Hardened concrete permeability determined according to the Bureau of Reclamation procedure, is illustrated in Figure 5.3.2. [36]

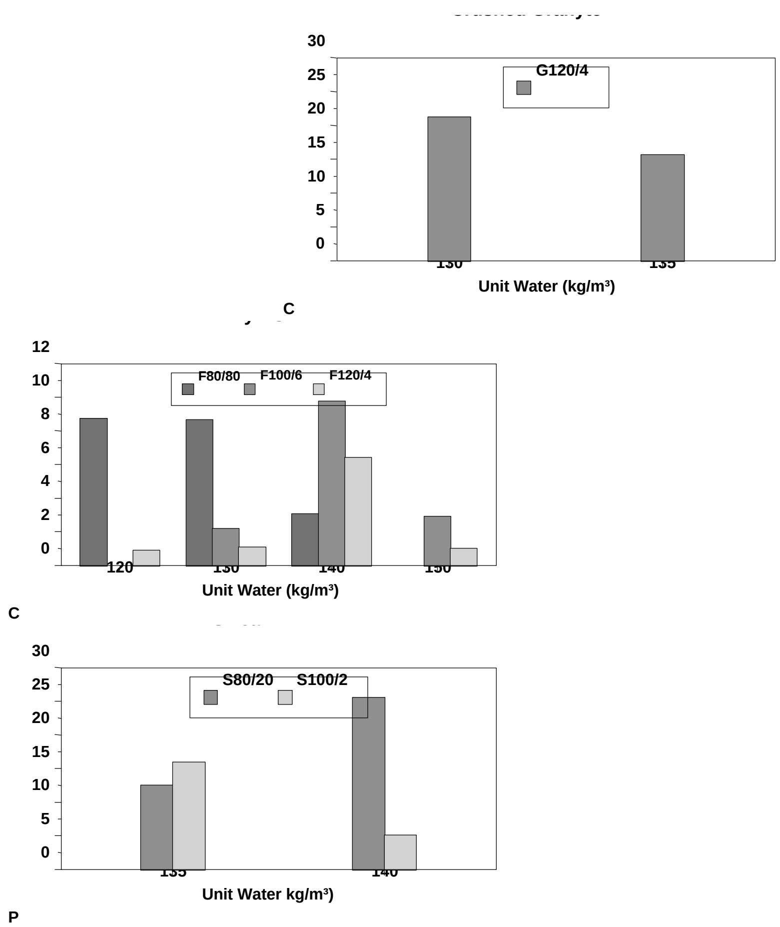

Figure 5.3.2 – Hardened Concrete Permeability

6- RECOMMENDATIONS

The authors strongly recommend the use of Grain Size Curve combinations that produce “closed” and cohesive mixtures with special attention to the fines content.

The kind of fines adopted will depend on the convenience at each job but it is wise to remember that the choice should be made on technical and economic basis.

The compaction ratio parameter is an element for evaluating the Quality Control performance and should be used as a warning, even when the minimum Specific Density required is much lower than the theoretical mixture.

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