PROPERTIES OF COMPACTION REACHED IN THE ROCKFILLS OF THE EL CAJÓN DAM

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ABSTRACT: This paper includes the properties of compaction reached in the rockfills of the El Cajón Dam, as much of the test embankment constructed previous to the bid, that was used as base for the design and specifications of construction of the curtain, and the one constructed by the contractor to determine the properties reached with its equipment, previous to be used in the construction. The properties reached in the body of the curtain are also described. The compaction properties are expressed in dry densities and void ratio, and the mechanical properties in static and dynamic modules of deformation, and in Poisson ratio. The results show that the properties considered in the design and the specifications of construction were conservative, with respect to the properties reached in the construction, which guarantees good behavior of the dam during its operation.

Key words: Compaction of rockfills.

1 Background

The studies of materials carried out previous to the bid for the construction of the curtain of El Cajõn Dam, included geological aspects of the rock bank El Vertedor, laboratory and field tests to determine the properties of the rockfill materials. The geological studies included surface studies, drillings, geophysical prospection and determination of available volumes of the rockfill; the particular studies of the rockfill consisted of the excavation in the bank, test blastings, construction of a test embankment with different layer thicknesses and roller passes, field and laboratory tests to estimate granulometric properties, densification, module of deformation and the shearing strength on compacted materials (Report of CFE 2002[a]).

The test embankment was carried out in two stages. During the first stage a plain vibratory Roller with 7.5 tons of static weight was used, together with rocks extracted from the first 18 mts depth.

In the second stage, a 10.6 ton roller was used, together with material from major depth and better quality. In both cases the rock used was ignimbrite identified in the project as TicU3, which was extracted directly from the excavations, without processing. It was built in layers of 0.90 m, 0,60 m and 0,40 m thickness when loose and compacted with 4, 6 and 8 passes, adding water as specified (200lt/m3). The dry density and number of passes were determined excavating 61 giant volumetric pits in the first phase and 43 in the second.

Confined plate tests were also carried out to obtain the module of deformation and permeability tests Matsuo-Akai type, as well as seismic refraction tests to determine the dynamic modules.
The tests showed:

1) In general, the dry densities of the competed rockfill increase with the roller weight and the number of passes, and decrease with the growth of the layers thickness.
2) The results are somehow erratic in the case of the layers with higher thickness.

3) Although the rock of the first stage was of lower quality, since it was extracted from minor bank depth, and in the second stage the quality was higher corresponding to a major exploitation depth, no remarkable discrepancies were observed between the results for both stages.

Considering the results of the test embankment and those of corresponding to analysis through finite elements under static and dynamic loading, and considering construction and economic aspects, the final zoning of the curtain was determined (Figure 1) and the specifications of construction with the material characteristics 3B, T and 3C were stated, indicating the use of a plain vibratory roller with 118kN of minimum static weight in the drum, use of 200 lts of water for each m3 of rock, with a loose layer thicknesses of 0.80m, 1.00m and 1,40m, respectively, corresponding to a maximum particle size of 0.65m, 0.80m y 1.10m, respectively for each material, all of them compacted with 6 number of passes of the indicated roller (Report CFE2000b)

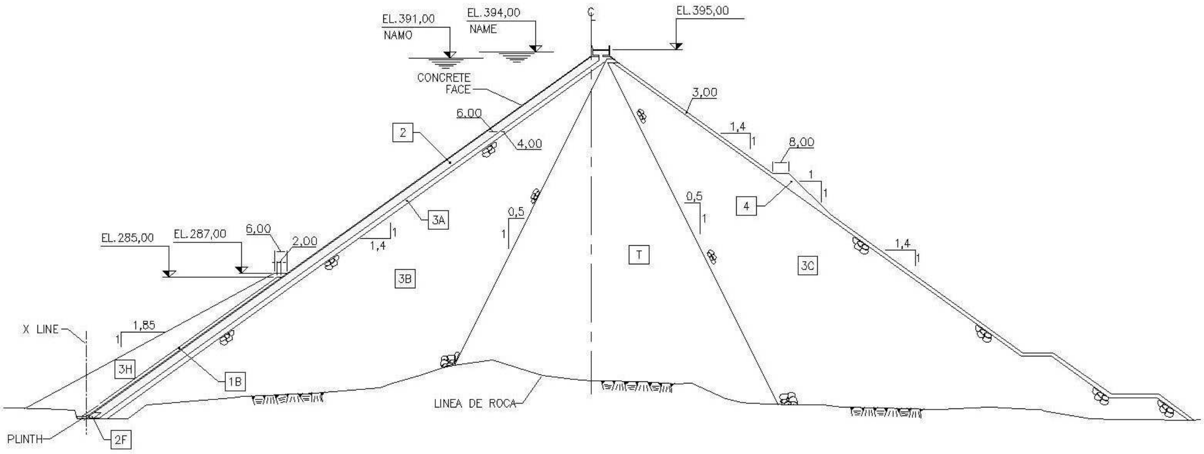

Figure 1. Cross section and curtain zoning

In the Specifications of the Construction for the civil works, it was stated the obligation of the Contractor to build a test embankment previous to the beginning of works, for the rockfill materials 3B and T, as well as to determine the properties fulfilled with the compaction equipment that would be used during the construction, by means of pits and tests directly on the test embankment.

2 Construction of the test embankment

2.1 Objectives

The firm Constructora Internacional de Infraestructura, S.A de C.V (CIISA), built the test embankment wtih the following purposes (CIISA, 2003) along with the the philosofy of the proper specifications and ideas to confirm the utility of this practice:

1) To carry out placement and compaction tests for 3B and T materials, using the specified criteria and construction equipment.
2) To assess the efficiency of the vibratory roller to be used in the construction of the curtain, considering the thickness of the layers and number of passes of the roller for each type of material.
3) To determine the dry densities of the compacted rockfill, void ratio, granulometries of the materials and limits of consistency of the fine material (passing Sieve N”40), by means of giant pit excavation.
4) To calibrate the compaction indicator seismograph type (named compactometer) attached to one of the rollers.
5) To check that the exploitation procedure of the bank and processing of 3B and T materials are

adjusted to the specified granulometries

6) To run two permeability Matsuo-Akai tests in the sixth layer of 3B material and one in the sixth layer of T material, in both cases alter six (6) roller passes.
7) To run seismic refraction tests, to determine the rigidity and elasticity modules in the sixth layer of 3B material in the test embankment and in the first layers of T material, directly into the curtain.

2.2 Rock materials and blasting tests

The test embankment was placed in a location where a surface level, with approximately 100 m long and 85 m wide was possible to set up, with adequate accesses to the quarry and the necessary space for truck manoeuvres. The final dimensions were 55x70 m at the base with slopes 1.4 H: 1.0 V, and consisted only of 3B material.

Rocks from the aduction channel of the spillway was used, identified as ignimbrites TicU3, also used in the test embankment, considered to be representative of the one employed in the curtain construction. During the proper excavation, blasting tests were carried out to define the adequate grid of holes and the quantity of explosives to produce the granulometric curve of 3B, T and 3C inside the specified band.

The water added to the rockfill was taken out of the Rio Santiago, following the specifications for the construction of the civil Works. Flowmeters were used to get an average consumption of water in the proper test embankment.

2.3 Compaction equipment

For the compaction, an Ingersoll-rand IR SD-200DX plain vibratory roller was used, self-propelled, with 121.6 kN (12.4 Ton) static weight in the drum of 1.65 m diameter and 2.13 m wide, with a vibration frequency of approximately 1850 rpm.

A compaction indicator (compactometer) attached to the roller was used, Standard Compactometer ALFA-022R-000E, Geodynamik (CIISA, 2005) calibrated during the construction of the embankment through the compaction value (CMV), which results to apply the principle of Fourier, one compound signal can be rerpresented by a sm of the fundamental frequency ovf vibration and a number of harmonics. The CMV (compaction number) is defined as the not dimensional relation between the value of the amplitude of the fundamental vibration mode and the amplitude of the first harmonic.An amplitude rises with the increasing rigidity of the rockfill.

The average speed of the compaction equipment was 3.4 km per hour and it kept uniform, with an average vibration frequency of 30 Hz (1800rpm)

2.4 Procedure adopted for the works

2.4.1 Preparation for foundation

The test embankment foundation called compacted and levelled base was formed with a rock layer 3B of 0.5m minimun thickness, necessary to level the area and founded on rock material.

2.4.2 Tests performed

The tests performed are indicated in Table 1 and consisted of:

1) Compaction tests in 3B material, layers of 0.80m thickness, maximum grain size of 0.65m, with 4, 6 and 8 vibratory roller passes in eight layers that allowed to execute 80 volumetric pits.
2) Compaction tests in T material, placed directly in the curtain in layers of 1.00m thickness, maximum grain size of 0.80m, where 26 pits were carried out.
3) The density, void ratio and granulometric of rockfill were determined with the giant pits excavation, with an adjustement in the shape according to experiences at the site. These rectangular pits had 2, 00 wide and 3,00 long with sub-rounded borders to permit its excavation with a retro-excavator . Each sampler had a volume superior to 4.0 m3

according to the shape in which the pit bottom was formed.

4) Permeability tests of the Matsuo-Akai type; 2 (two) in 3B material and (one) in material T, in both cases after compacting with 6 roller passes, or the Mansur-Kaufmann formulae.
5) The density of solids were determined in the three fractions- the sandy fraction, the gravel and sizes >3”, according to the instructions of Bureau of Reclamations (standard 5320-89) similarly to the ASTM standards D854-83 and C-127-88.

Rock Material	Number of passes	Number of layers	Number of pits	Dry density of the rockfill	Dry Density of the rock	Granulometrics	Permeability Matsuo-Akai
3B	4	8	25	25	11	16	
3B	6	8	28	28	14	20	1
3B	8	8	27	27	10	15	1
T	6	10	26	26	17	32	1
Total			106	106	52	83	3

Table 1. Tests performed in the different types of material to have an idea of the numerous activities to be planned.

2.4.3 Sequence of works

The dimensions of the test embankment are shown in Figure 2. The compaction bands were of 2.25m wide, with a side superposition of 0.5m. The procedure to verify the influence of the number of passes was established through topographic surveying control.

The sequence of operations was as follows:

1) The topographic control points were marked over the base layer surface, placed as it is shown in Figure 3. Fifty six (56) measurement points were defined, enough to fulfill statistic representation, taking care to place them out of the pit excavating areas.
2) The material compaction was arranged in sittings of two passes, with topographic measurements after each sitting. In this way, measurements at 2, 4, 6 and 8 passes were registered.
3) Once the programmed passes for the first sitting in the first layer of 3B material were completed, the giant pits were excavated according with the distribution shown in Figure 3.
4) The dry densities of the compacted rockfill determinations were carried out using a plastic membrane to impermeabilize the surface and filling the hole with water to measure the volume, similarly to the well known Oroville method.
5) Once the tests were finished, the pits were filled with rock in two layers of 0.4m thickness, with roller passes, taking care to limit as much as possible the area close to the pit, without affecting the compaction in the neighboring areas.
6) Before placing the new layer, the points for topographic control were positioned again, registering their respective elevations.
7) The geophysical studies consisted of 6 lines of Seismic Refraction laying (TRS) in the sixth layer of 3B material, in zones of 4, 6 and 8 roller passes, divided in axis 5, 11 and 18. With the results of compressional and shear waves, Poisson’s ratio, Elasticity and Shear Modulus were established.

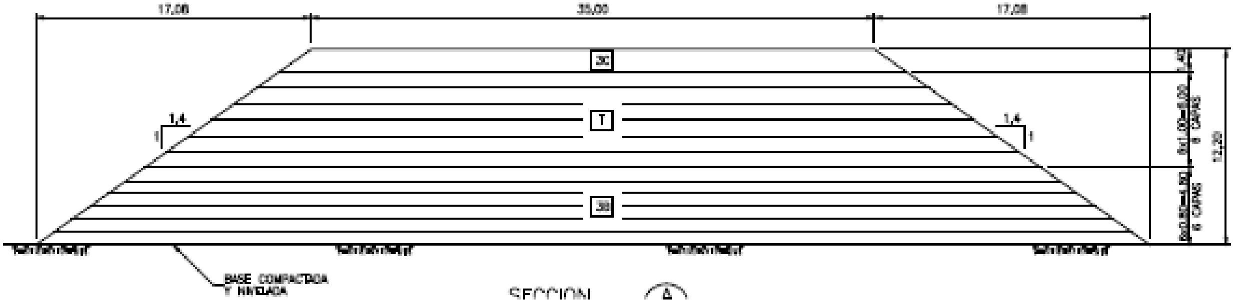

Figure 2. Dimensions of the test embankment.

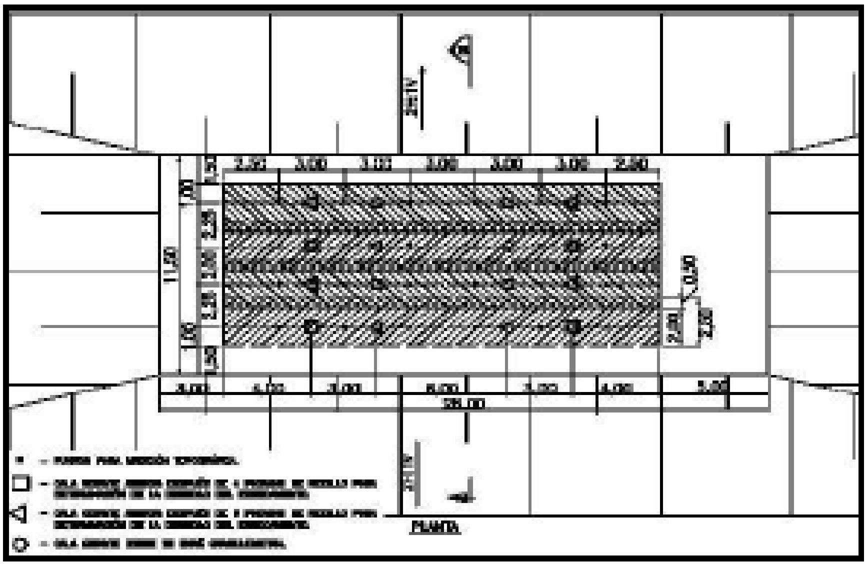

Figure 3. Proposal for location of pits

3 Presentation of results

Based on the results presented by the construction firm (CIISA, 2004a, b and 2005), and the field observations performed by the staff of supervision of CFE at the curtain, the following analysis are presented.

The relationships between the density, the number of passes, the percentagem of sands, gravel and blocs, the layer thickness before compaction were some of the most important factors to support the decisions to adjust and define the requirements for the construction of the curtain.

3.1 3B Material

In order to assess the efficiency of the compaction fulfilled by the roller in different number of passes, based on topographic measurements, the values of settings for 2, 4, 6 and 8 passes were determined.

Some results of the second layer are presented in Figure 4. In these graphics, it is possible to observe that the highest efficiency of the equipment is reached between 4 and 6 roller passés and after this, the curves tend to be asintotic, showing that efficiency decreases; in general the response was similar for the rest of the cases.

The specific values of settings for 2, 4, 6 and 8 passes were also calculated as a percentagem of the medium-thickness of the layer before compaction. These results are shown in Figure 5. In these figures, it is observed that in the first 2 passes, a 30% setting medium average from the whole and for 6 roller passes 85% from the whole is presented. The specific setting value for 6 passes is of about 7.2% in relation to the layer thickness before roller compaction.

Some studies developed by Dynapac show that in case the setting in the last two passes of equipment is less than 10 mm, it can indicate that the reached compaction is adequate.

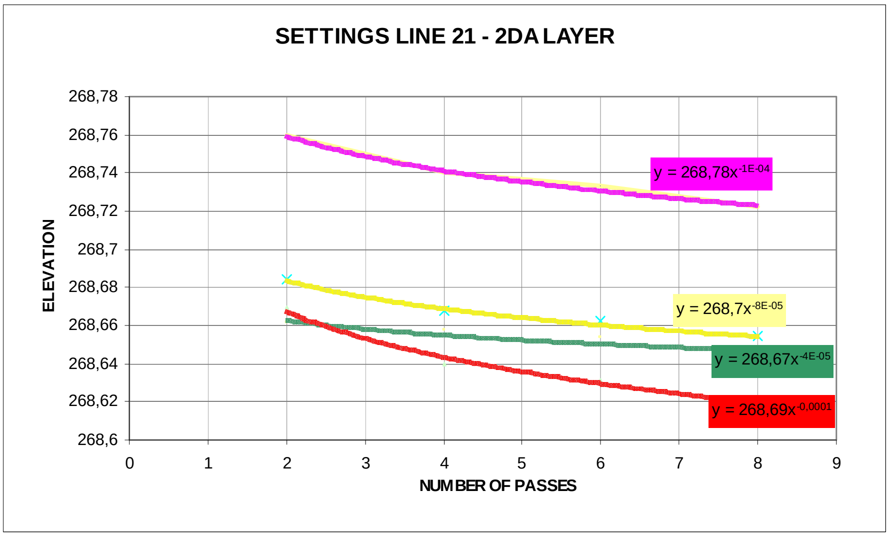

Figure 4. Settings resulting from compaction in line 21 with passing of plain vibratory roller o f 12 ton in the test embankment, on 3B material with 80cm loose layer thickness

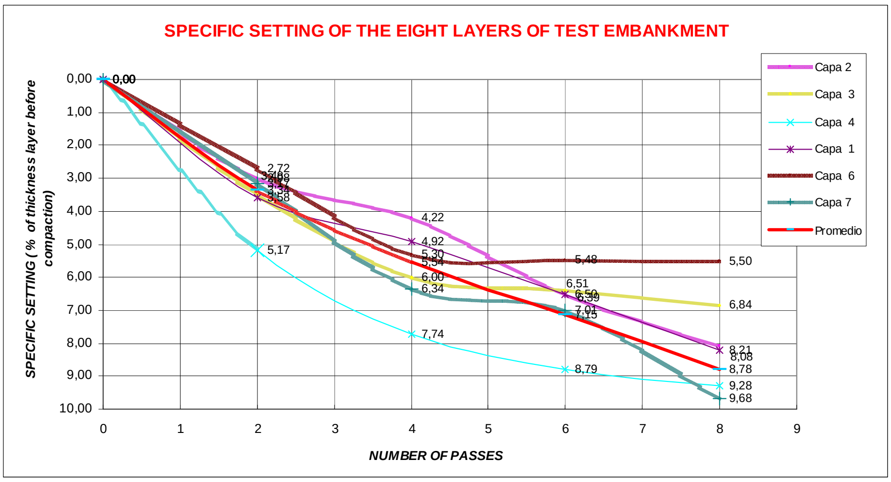

Figure 5. Settings related to original thickness resulting from compaction in each layer of 3B material with passing of 12 ton plain vibratory roller in the test embankment

In the next Figure 6 is shown the dry density (dry volumetric weight) variation of the rockfill, fulfilled according the number of passes. The dry densities are about 1880 kg-m3 (18.8 kN-m3) average for 6 roller passes.

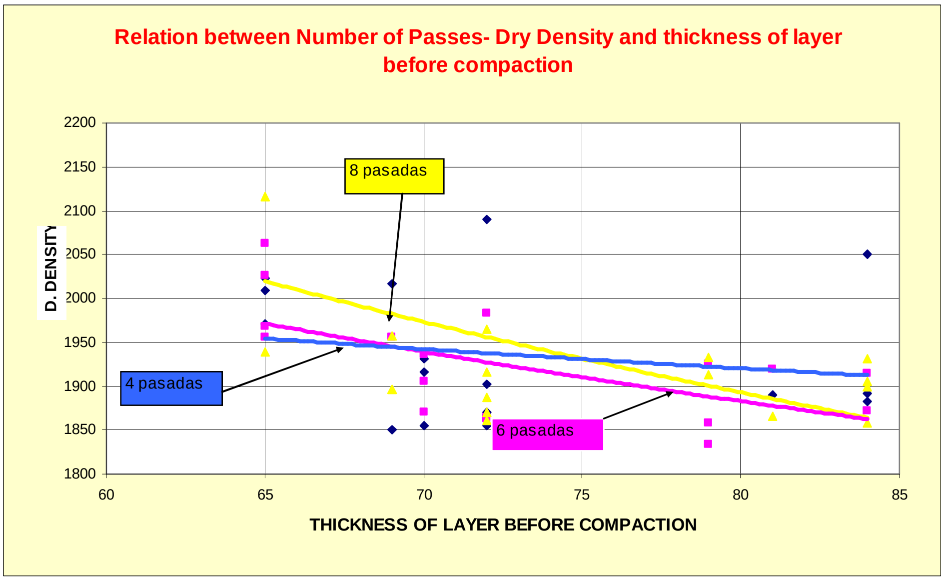

Figure 6. Variation of dry density according to the number of passes of the 12 ton plain vibratory roller passes with different loose layer thickness

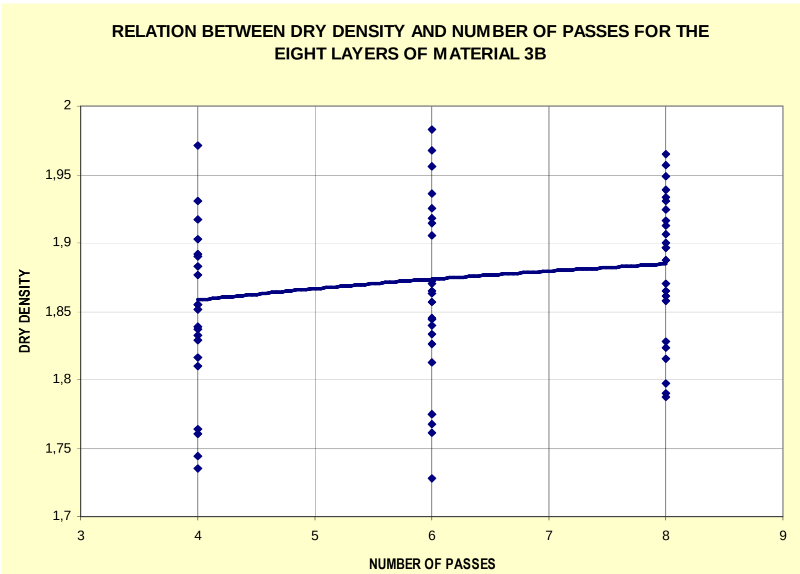

Figure 7. Variation of dry density according to the number of passes of the 12 ton plain vibratory roller passes on 3B material with 80 cm loose layer thickness

The total void ratio (et) and effective void ratio (ee) related to the number of passes are presented in Figure 8. The et was determined considering Ss=2.60 (average) and the ee, in the rockfill, was stablished considering Ss=2.34 for rock fragments bigger than sieve No 4.

The et considers the rockfill structure cavities and the rockfill fragments internal cavities, while the ee only refers to the former, that is, the ones resulting from the structure (arrangments) of the rockfill after compaction, without considering the porosity of the rock fragments. The et for 6 passes reaches an average value of 0.38, while the average ee for the same amount of passes is 0.26.

The rockfill mechanical behavior is mainly determined by the ee, even though, it must be considered that when the difference between ee and et increases, the grain breaking due to rock porosity also increases; however, for the study of the present case, this is not regarded as an important value.

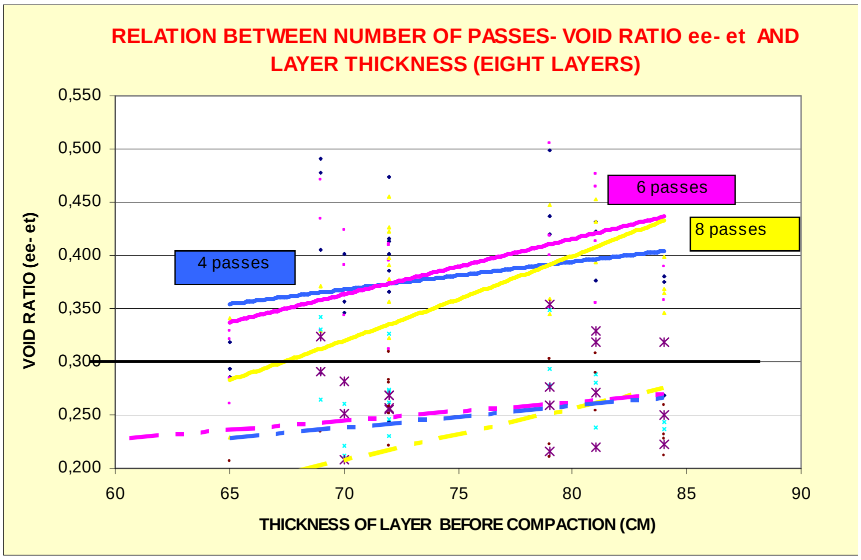

Figure 8. Variation of total and effective void ratios et and ee according to the number of passes with different loose layer thickness

According with Marsal (1972) and Cooke (1982) for well graduated rockfill with a low void ratio, defined as less than 0,30, the contact forces between particles is small and the breaking particles is low.

Except for layers 1 and 2, where two samplers do not fulfill the specified granulometric band and other four exceeded the fine percentage (>5%), all the other samplers fulfilled the granulometric range.

Figure 8 shows the average granulometric curves for each of the compacted layers.

The two permeability tests carried out in this material indicated a high level of permeability, using the Mansur-Kauffman trench method, resulting an approximate permeability coefficient of 87 and 104 cm/s (CIISA, 2005).

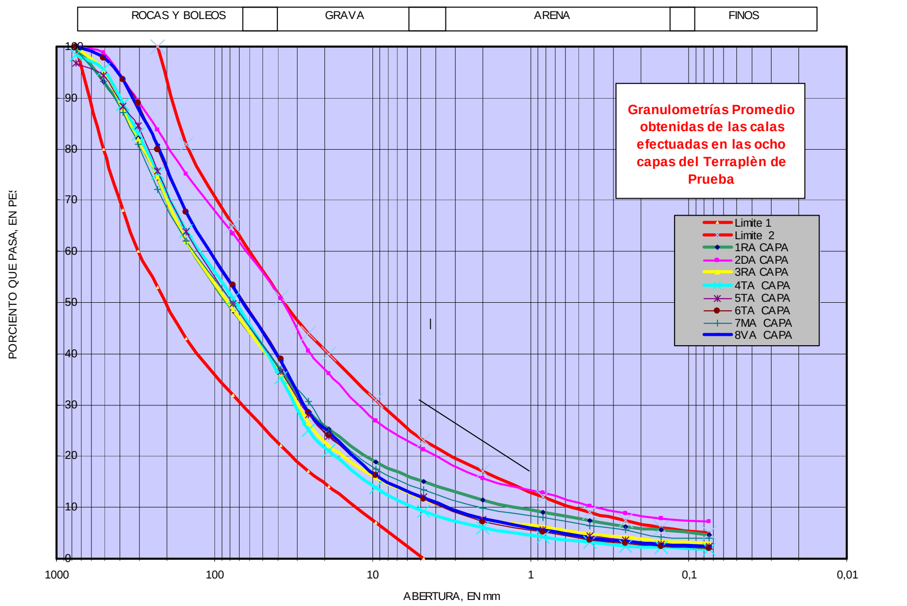

Figure 9. Average granulometric distribution of 3B material in the eight compacted layers

The seismic refraction studies performed by the end of the sixth layer, stated the variation of Poisson's ratio in relation to the embankment depth (Fig. 10), resulting an average value of 0.36 for six passes, showing a light decrease with the layers depth.

At the same time, with the results of seismic refraction layings, it was possible to obtain the elasticity (E) and shear modulus (G) in relation to depth (Figure 11) and to the number of roller passes (Figure 12), resulting an average value of 90 and 250 MPa, respectively, for six passes. These values increase with the depth of the layers.

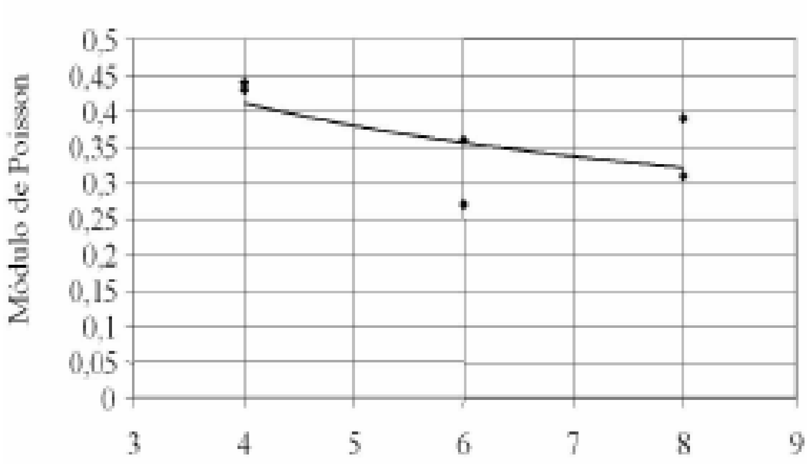

Figure 10. Variation of Poisson's ratio according to the number of passes

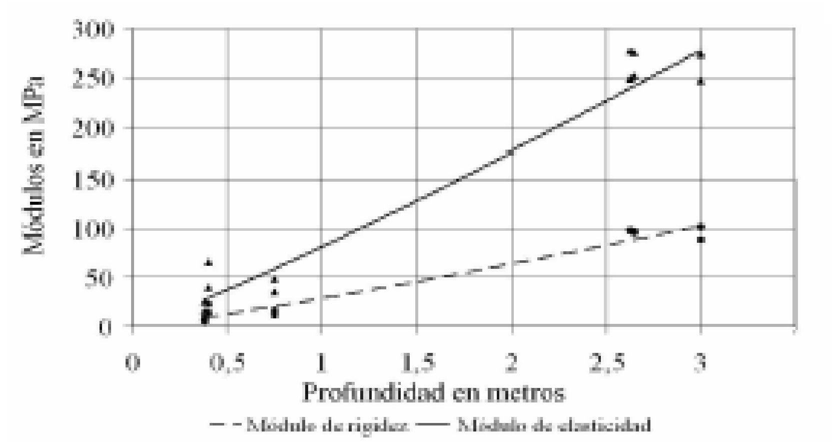

Figure 11. Variation of Elasticity and Shear Modulus according to the depth of the layer

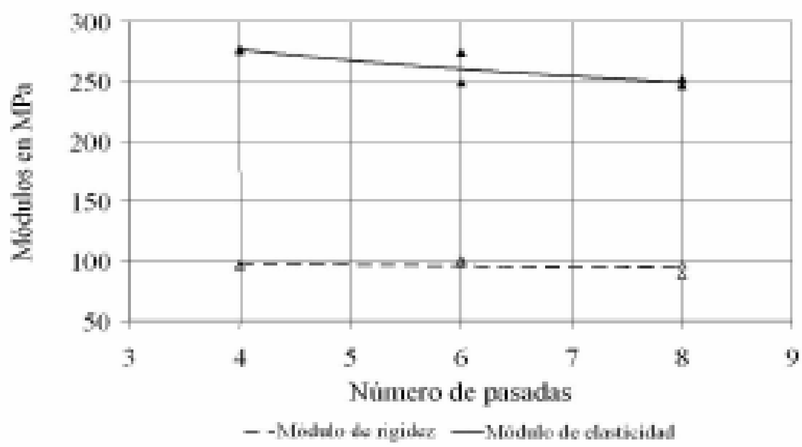

Figure 12. Variation of Elasticity and Rigidity Modulus according to the number of passes

The CMV compaction value obtained with the compactometer attached to the equipment was of about 35 for six roller passes.

3.2 Material T

Twenty six volumetric pits were carried out in T material, placed directly in the curtain body. The dry densities results, variation and average in relation to the number of tests performed, are presented in figure 14, which shows an average of 1846 kg-m3. The et and ee variation is shown in figure 15, resulting an average of 0.41 for et and of 0.29 for ee. As with the two permeability tests performed in 3B material, the one carried out in T material showed a similar high permeability.

The variation of elasticity and shear modulus, obtained through the TRS in three different levels of the curtain rockfill (228, 235 and 253m) are represented in graphics as depth function in figure 16. These modulus increase with the depth of the layers; the variation of the modulus show a tendency to a constant value at 25 m depth, resulting 380Mpa for G and 1000MPa for E.

The CMV compaction value obtained with the compactometer attached to the equipment was of about 32.5 for six roller passes (35 for the 3B material).

4 Conclusions for material 3B and T

On the basis of the results obtained in the test embankment, it is assumed the next construction aspects and parameters in both materials. The properties fulfilled with the indicated number of passes are adequate for the behavior of the curtain since they are favourable in comparison to those considered in the design (II-UNAM, 2002).

Construction Aspects	**3B**	**T**
Loose layer thickness (cm)	80	100
Maximum grain size (cm)	65	80
Number of passes of 12 tons roller	6	6
Maximum fines (%)	5	5
Water quantity (lts/m3)	200	200
Parameters considered in the design of CFE (2002)		
Layer thickness	80	100
Void ratio	0,28	0,30
Poisson ratio	0,35	0,35
Modulus of deformation (Mpa)	45	35
Average properties reached in the test embankment		
Dry Density (kg/m3)	1880	1846
Total void ratio et	0,40	0,41
Effective void ratio ee	0,28	0,29
Poisson ratio	0,36	0,36
Dynamic rigidity modulus (Mpa)	95	50*
Dynamic elasticity modulus (Mpa)	260	130**
Compactometer Value (CMV)	35	32,5
Average properties reached in the curtain during the first reports of the instrumentation		
Modulus of deformation (inclinometers)		145
Modulus of deformation (hydraulic cells)		241

*Dynamic rigidity modulus (G) 50 MPa and **Dynamic elastic modulus (E) 130 MPa, two meters under the surface.

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