ICOLD Symposium on Sustainable Development of Dams and River Basins, 24th - 27th February, 2021, New Delhi

GEOTECHNICAL CHARACTERIZATION OF CEMENT BENTONITE MIXTURE FOR SEEPAGE CUTOFF WALLS IN ITUANGO DAM

Z. ZAPATA, M.C. SIERRA AND L.F. RESTREPO
Integral Ingenieros Consultores, Medellín, Colombia

J.E. MÚNERA
Consulting Engineer, Medellín, Colombia

ABSTRACT

In April 2018, when the emergency period of the Ituango Hydroelectric Power Project began by an obstruction in the diversion system and subsequently the river was routed through an unfinished water conveyance structures, the construction of the rockfill dam was at an elevation of 385 masl (meter above sea level). This in itself represented a risk for the project and the communities in its area of influence, taking into consideration that for the operation of the spillway, the dam needed to be at least at the level 405 masl, and became mandatory to take actions to prevent an imminent overtopping. In this case, the construction of a "priority fill" was defined, which finally reached the 418 masl level and subsequently a cement-bentonite cutoff wall was constructed in the middle of the embankment. The construction of the barrier sought to restrict the flow of water through the dam, as the impervious core was not built from 385 masl. This paper details the test program implemented to characterize the cement-bentonite mixture, to make it compatible in terms of stresses and strain with the rest of the body of the dam.

1. INTRODUCTION

Ituango Dam is an earth core rockfill dam ECRD on the Cauca River, Northwest of Antioquia, Colombia. Ituango Dam is a 240 m high (final elevation 435 masl), crest width of 15 m, freeboard zone of 15 m and a crest length of 480 m. Additionally, its slopes are 1.75:1.0 in upstream and 2:1 in downstream (horizontal to vertical). The material core 1A is a combination of gravel, silty and clayey sands (maximum sizes of 6 "), with a mean value of plasticity index 6%, percentage of fines 22% (Integral Ingenieros Consultores 2019) and the core was projected to have a width of 12.0 m in the upper part of the dam. The elastic modulus of 1A was determined by triaxial tests and calibration with instrumentation, finding values close to 30 MPa in the area of the priority fill. In this sector, the 3B material has a maximum size of 30" and the percentage passing through the No. 200 (75 µm) sieve close to 4%; the elastic modulus is about 60 MPa.

On April 28, 2018, when the dam had only reached level 385 masl, the river diversion system suffered an obstruction that represented the unscheduled filling of the reservoir, diversion through the water conveyance system (without having completed the headrace tunnels, penstocks, powerhouse, surge chambers, among others). The construction of the priority fill became necessary to allow the operation of the spillway (unfinished, until that moment), from the level 405 masl. On July 19 of the same year, the priority fill reached level 418 masl with modifications to its initial design. These changes allowed to increase the construction rate and thus control the risk of overtopping.

The initial idea was that the priority fill could be removed later; however, as the contingency evolved, the inconveniences and risks of dismantling it were analyzed, considering that this process involved reducing the freeboard and limiting the operation of the spillway. In consequence, a definitive solution was executed to reduce the seepage occurring at that time downstream of the priority.

The chosen solution was a set of cutoff walls, a central barrier and four in the abutments, which improved the waterproofing system between elevations 418.0 masl and 385 masl, abscissa km 0+123 at km 0+639 of the dam. In total, 230 panels of 2.8 m of width, modulated every 2.2 m were built for the central barrier. This approach also generated a connection with the core built before the contingency. The location of the central cutoff wall, over the maximum dam cross-section, is shown in Figure 1. In the period of the construction of the central curtain, the only path discharge of the river was the water conveyance system, which between January and February 2019 also had to be closed due to effects caused on the rock mass.

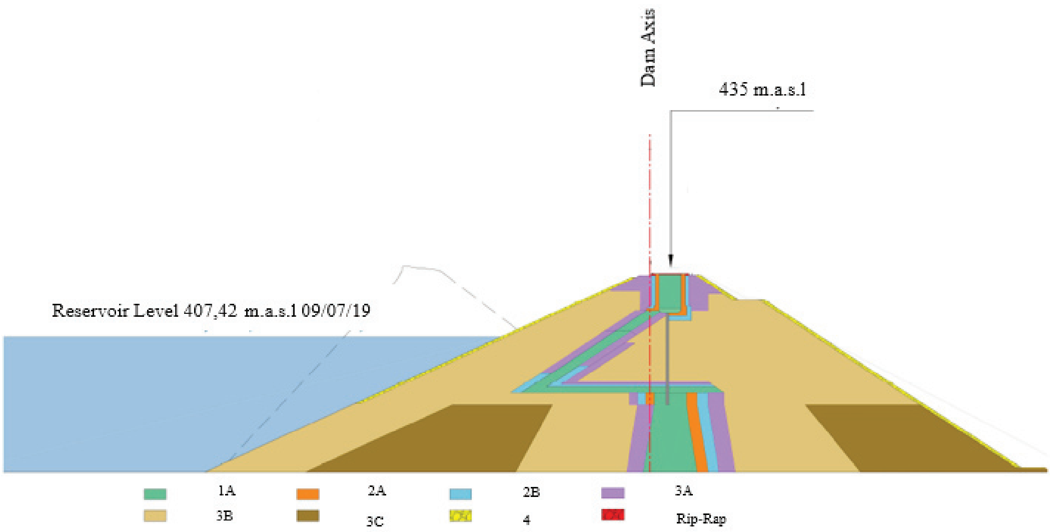

Figure 1 : Modifications to Ituango Dam, including the central cutoff wall in the cement-bentonite mixture. Image modified of Consorcio Ingetec Sedic (2019c).

The others feature of the cutoff walls of Ituango Dam are:

- Thickness1,0 m.
- Embedment in the core 5,0 m.
- Mixture: cement/bentonite/water and additives.
- Barriers in abutments are 1.0 m in thickness, covering up to 19 panels in the left abutment and 9 panels in the right abutment. The maximum depth was 38 m to the limit with the existing terrain. The connection between curtains and foundations was made through contact and consolidation injection.

2. GEOTECHNICAL CHARACTERIZATION

2.1 Criteria for design

Typically, this type of cutoff walls has been implemented in foundations or very permeable abutments. There are not sufficiently documented cases of cutoff constructed in the upper part of a dam, without extending to the foundation and crossing the entire valley. Therefore, for the verification of the mechanical performance of the Ituango cutoff walls and its compatibility with the rest of the rockfills zones, filters and the core, a wide program of tests and complex numerical simulations has been developed, taking into account the static, dynamic and seep conditions. This document details the laboratory and field tests executed to meet the design considerations. Details of the numerical modeling and installed instrumentation (piezometers, magnetic extensometers, among other necessary elements to record the final behavior of the barriers) are given in the official project documents (Integral Ingenieros Consultores 2019).

After different analyses, it was concluded that compatibility of stresses and strains, between the curtains and the fill zones, refers to the fact that, under the static condition, the dam is expected to suffer settlements until its completion (435 masl) and due to a long-term behavior. This means that the cement-bentonite mixture should be able to accompany the strains experienced by the body of the dam, without cracking excessively and, therefore, without suffering excessive increases in its permeability. Thus:

- The cutoff walls cannot behave as rigid elements, compared to the response of the surrounding rockfill zones, filters and core of the dam. Therefore, sections with low flexural rigidity were adopted and with mechanical properties characteristic of flexible curtains. Based on the above, ranges of variation for the unconfined compressive strength UCS (ASTM D2166), elastic modulus E and hydraulic conductivity/permeability k (ASTM D5084) were defined and these were used as reference for quality control in specimens tested after 28 days of curing (samples were taken at the exit of the digester).
- Regarding the UCS, a mean value of 0.8 MPa was defined with a maximum coefficient of variation of 15%.
- A mean value of 250 MPa was established for modulus E as well as a maximum coefficient of variation of 40%. Modulus calculated as the slope around 50% of the failure load.
- The permeability k should be lower than 5e-8 m/s.
- Besides, the axial strain at failure was studied by consolidated undrained triaxial tests (ASTM D4767).
- On the other hand, the ASTM C348 test was adopted to find the flexural strength of the cement bentonite mixture. The central cutoff wall can be understood as a beam simply supported at ends (in this case, the abutments), considering the deflections undergone by the curtain inside the body of the dam.

- The above characteristics must be maintained over time, so the mixture was also subjected to the Pinhole test (ASTM D 4647).

Under dynamic loading, the beam concept is still applicable, however, in this case, the greatest displacements are expected in transversal direction to the crest length. Again, it is also necessary significant strain at the failure to accompany the response of the dam, due to the occurrence of an earthquake, without suffering excessive cracking and without having an exaggerated increase in the permeability of the material.

2.2 Cement bentonite mix design

According to Consorcio Ingetec Sedic (2019b), the contractor found that a mixture with a cement/water ratio about of 0.45, met the design requirements (mean proportion: water 860 kg / m^3, bentonite 29 kg, cement 387 kg, additive Eucon Forza-S 300 4.26 kg). During the elaboration of the mixture, the viscosity of the cement-bentonite slurry was between 31 and 59 sec, the decantation less than 5%, the density between 1.26 and 1.32 g / cm^3, and the pH of bentonite and water between 6-9.

2.3 Quality Control

From Figure 2 to Figure 5, statistics of UCS, modulus E and permeability k per batch control, are presented according to Consorcio CCC Ituango (2019). Following the technical specifications, at least three results should be obtained by daily production. In the course of that sampling, over 374 results per batch control and between 748 and 1122 for individual tests, were collected.

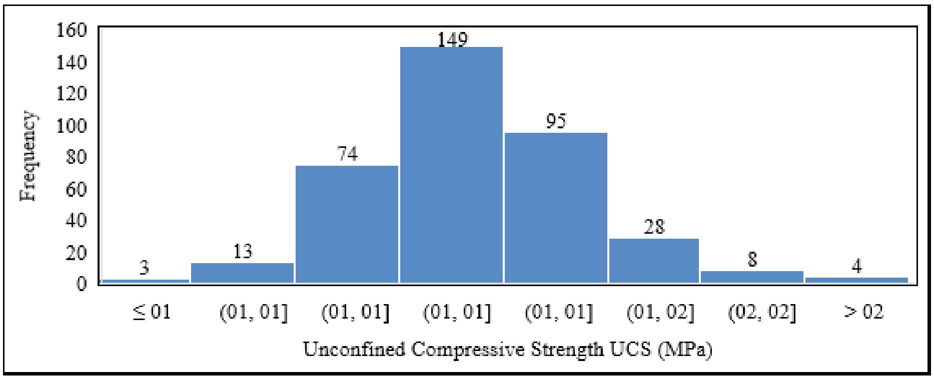

Figure 2 : Frequency histogram – unconfined compressive strength UCS.

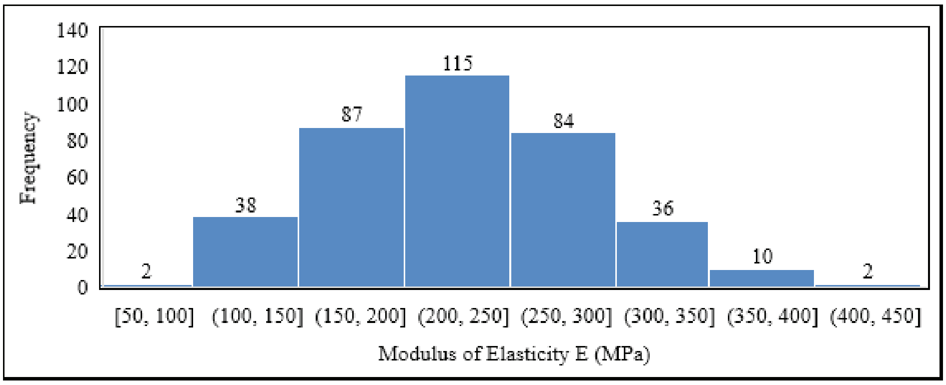

Figure 3 : Frequency histogram – elastic modulus.

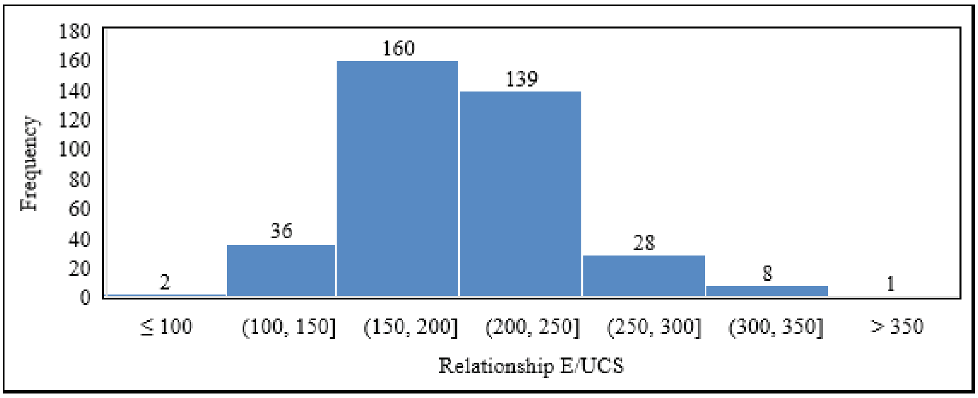

Figure 4 : Frequency histogram – modulus E / compressive strength UCS.

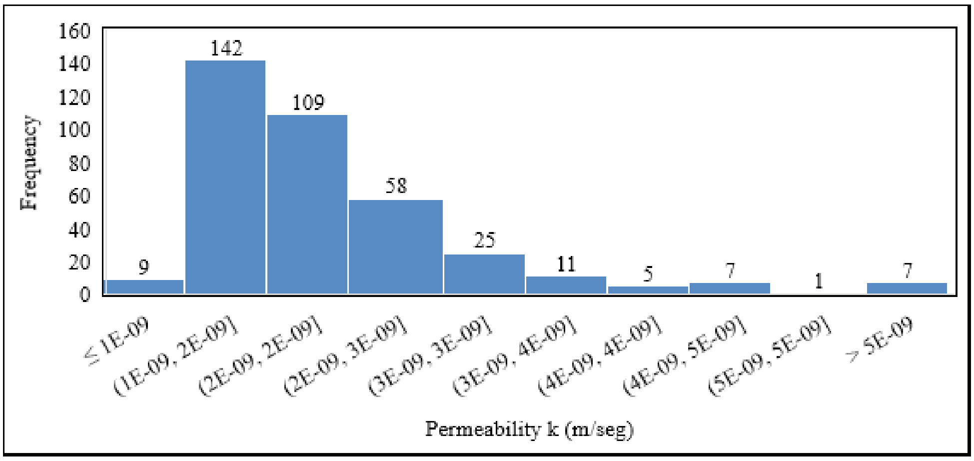

Figure 5 : Frequency histogram – permeability k.

In summary, the statistics for the modulus of elasticity E were:

- Mean value of E per batch at 28-days 228 MPa
- Range of variation for E 50-418 MPa
- Coefficient of variation for E 28.6%
  (five individual test results between 452 and 566 MPa).

Regarding statistics for the UCS, it underlines that:

- Mean value of UCS per batch at 28-days 1.14 MPa
- Range of variation for UCS 0.32-1.94 MPa
- Coefficient of variation UCS 36%
  (three individual test results between 0.32 MPa and 0.57 MPa). Those panels that do not meet the requirements should be re-excavated.

The relation modulus E/UCS was extracted from the database, to verify that the cutoff was configured as a flexible element:

- Mean value relation E/UCS per batch 200
- Range of variation for E/UCS per batch 70-369

Concerning the permeability:

- Mean value of k per batch at 28-days 1,9e-9 m / seg
- Range of variation for k 7,9e-10 m / seg -1,2e-8 m / seg

Finally, at least 13 Pinhole tests were carried out under ASTM D 4647, with heads varying between 2" to 40", on specimens with a diameter of 4.26 cm and height 3.85 cm. In these tests, the slurry was classified as ND or ND1 (non-dispersive clay with very light to no colloidal erosion under 15" or 40" head).

2.4 Triaxial tests

In total, five CU triaxial tests have been accomplished, with effective consolidation stresses σ3 varying between 150 and 780 kPa, which are represented in Figure 6 and Figure 7. Based on the results, a ductile behavior of the mixture to shear stresses was evidenced and, under σ3 simulated, the axial strain reached values of 7 to 10%, which corresponds to a wide range of ductility before failure.

The samples of panels 186 and 67 had ages between 56 and 59 days. For the other samples, the ages ranged between 150 and 180 days, at the time of the test. As marked in the curves, that axial strain at failure decreased with the age of the sample. On the other hand, the older samples reached maximum stresses before the ductile section, higher compared to younger samples.

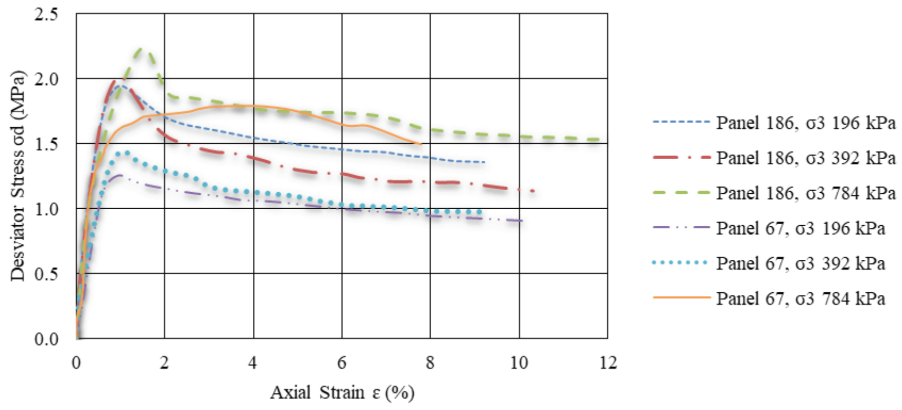

Figure 6 : Stress–strain relationship from consolidated undrained triaxial tests-part 1.

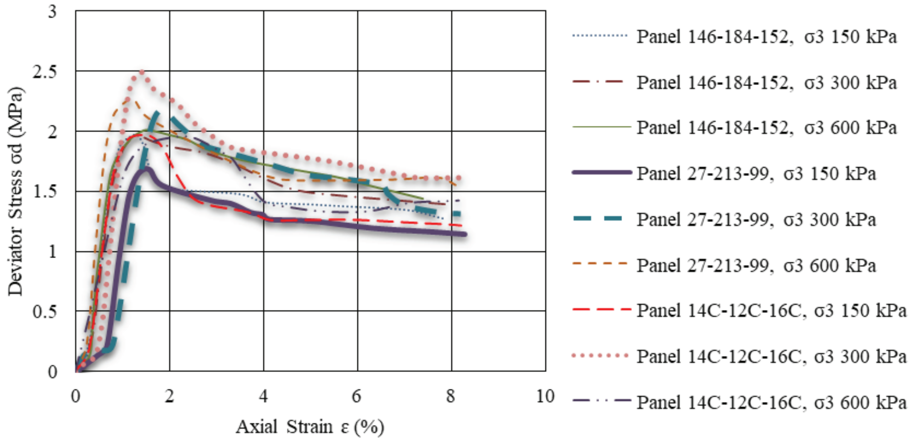

Figure 7 : Stress–strain relationship from consolidated undrained triaxial tests-part 2.

Regarding the shear strength, the collected information showed that the effective friction angle is above 18, while the effective cohesion exceeds 0.4 MPa.

2.5 Flexural strength

Flexural strength tests were implemented on 50 mm x 50 mm x 1.50 mm samples of the cement-bentonite mixture. In the absence of a specific standard for this material, the tests were performed under the parameters indicated in the ASTM C348 standard, with the difference that the center-loading device was not used (three supports). In this case, point loads were applied in thirds of the length of the beam (four supports). The assembly scheme is shown in Figure 8.

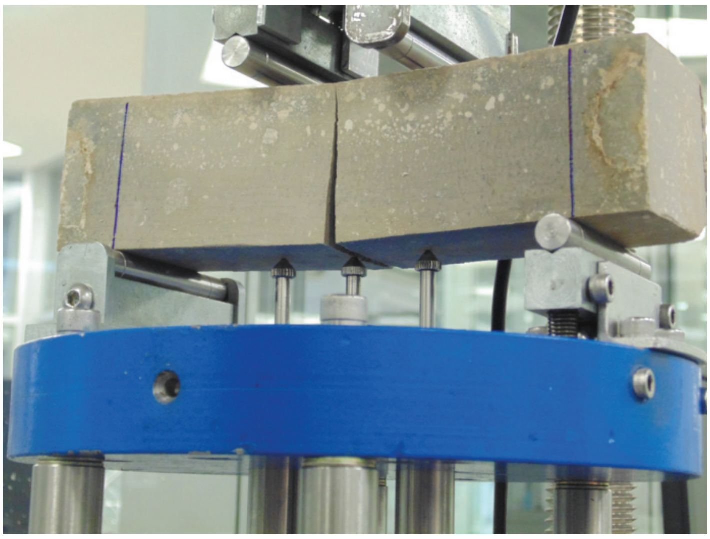

Figure 8 : Beam Testing Set-Up.

A fragile behavior under flexion in the cement-bentonite slurry was noted, that characterized by small strain before failure. The strain and flexural strength statistics for a total of 59 tests are shown in Table 1.

Table 1 : Flexural strength test-Statistics.

Parameter	**Age Days**	**w (%)**	**ρh (g/cm^3)**	**ρd (g/cm^3)**	**Δ (mm)**	**ε**	**MR (MPa)**
Mean	113	139,8	1,33	0,56	0,23	0,0024	0,7
Minimum	82	93,2	1,28	0,49	0,08	0,0009	0,3
Maximum	208	166,0	1,43	0,74	0,39	0,0041	1,3
Standard Deviation	37	14,7	0,03	0,05	0,06	0,0007	0,2

Where w (%) is the water content, ρh wet density, ρd dry density, Δ deflection, ε strain at failure and MR flexural strength.

2.6 Variation of permeability with axial strain

The variation in the permeability of the cement-bentonite slurry was evaluated, in the event of a cracking process. For this, on the samples extracted from the barriers material, CU triaxial tests were executed, until each sample reached an axial strain of 2% that is within the plastic range of the stress-strain curves. Once the desired axial strain was obtained, the hydraulic conductivity was measured. The findings are summarized in Table 2.

Table 2 : Permeability with 2% of Axial Strain.

Sample	**Effective Stress (kPa)**		**Deviator Stress (kPa)**	**Permeability (m/s)**
ID	σ3	σ1	σd	k
193	96,0	2032,2	1936,1	3,13E-08
194	281,7	2344,7	2063,0	4,31E-08
195	472,2	2537,2	2065,0	1,98E-08
279	132,5	1585,7	1453,2	6,07E-08
280	283,7	2423,2	2139,5	2,79E-08
281	509,0	2487,0	1979,0	5,81E-08
336	137,2	1775,4	1638,2	2,43E-08
337	260,0	2260,8	2000,8	1,01E-07
338	573,9	2882,4	2308,5	4,60E-08
Min.				1,98E-08
Max.				1,01E-07
Mean.				4,58E-08

In general terms and as far as permeability values are concerned:

- Only three of the results obtained from all the tests, specifically those executed on samples 279, 281 and 337, register permeability values higher than the maximum specification, that is, 5.0e-08 m / s.
- On the other hand, the mean of permeability calculated on cracked samples is greater than the mean value of the quality control, but in any case, this is of the same order of magnitude as the maximum specification.

2.7 Lefranc Test

Lefranc tests were reported in Consorcio Ingetec Sedic (2019a) for reservoir level 407.5 masl (data from March 31/2019). Before the tests, boreholes were drilled to a depth of 37.0 m and 1.0 m was left as a plug. In this case, permeabilities varied between 6e-8 m / sec and 6e-11 m / sec, for a total of four tests. Since the maximum specified permeability was 5e-8 m / sec, it was considered that the requirements given from the design were met.

2.8 Seepage chemistry characterization

With the construction of the cutoff wall, seepage in the downstream of the dam, related to the base of the priority fill was reduced to approximately 8 l / sec (data for the end of the year 2019). Given the occurrence of this remaining flow and considering the importance of monitoring any increase in the permeability of the barrier, it was also essential to generate control over some chemical parameters of the infiltrated waters and compare them with the reservoir data.

The chemical monitoring provides data on the trends over time of some key variables that may eventually be connected to mineral dissolution and probably, internal erosion. Such variables include pH, temperature, total dissolved solids TDS, conductivity, alkalinity, among others. According to Dam Safety Technology Development Program (2005) increases in the pH of the seepage may be associated to calcium solution and values greater than 9.0 may be related to grout contact. Sometimes, the temperature gradients between upstream and downstream can also be an indicator of the occurrence of leaks. Total dissolved solids may increase with elevation and contact for long periods with soil or rock. Electrical conductivity, on the other hand, is linked to the presence of dissolved electrolytes that conduct electricity in proportion to the concentration; it can be used to validate the quality of the analyzes since this variable on occasions can be approximated to the total dissolved solids. Finally, alkalinity is a variable that must be analyzed in conjunction with pH, especially in the presence of grout, among others.

The summary of the data taken so far in the seepage of the priority fill is shown below. According to the behavior of the variables in the time, which are summarized in Figure 9 and Figure 10, records should be continued to clarify their normal trend. As a preliminary interpretation, it should be noted that the pH of the seepage is among 7 and 8.4 which is a positive indicator of the low probability of dissolution of calcium or elements from cutoff walls material. Conforming to data available for different depths of the reservoir, the pH (in units) of the collected water is among 7 and 8.6 and in most cases, slightly higher than the values reported for the seepage. Significant differences do not occur in the temperature measured in both sites, the reservoir and downstream of the dam, as shown in Figure 9.

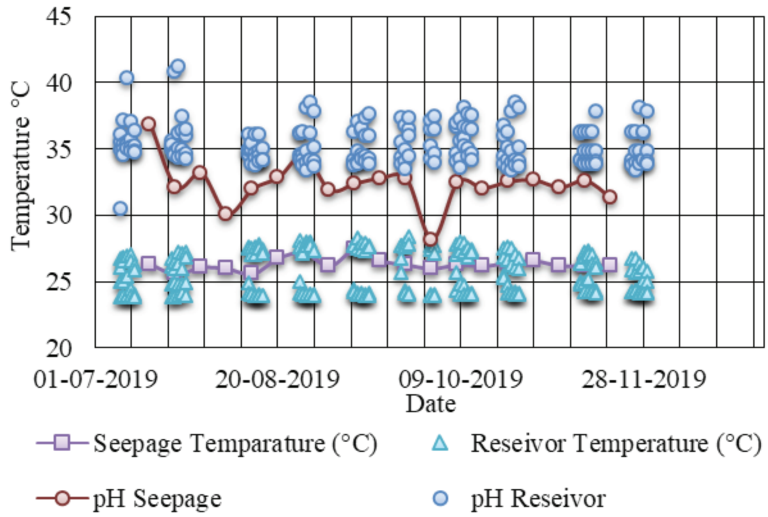

Figure 9 : Temperature and pH monitoring.

As reported in Figure 10, the concentration of total dissolved solids is below 340 mg / l, with a tendency to stabilize. On the other hand, the electrical conductivity presented a similar behavior to the TDS concentration for the first data; the calibration of this measurement will continue as, for the last part of the time series an erratic behavior was observed.

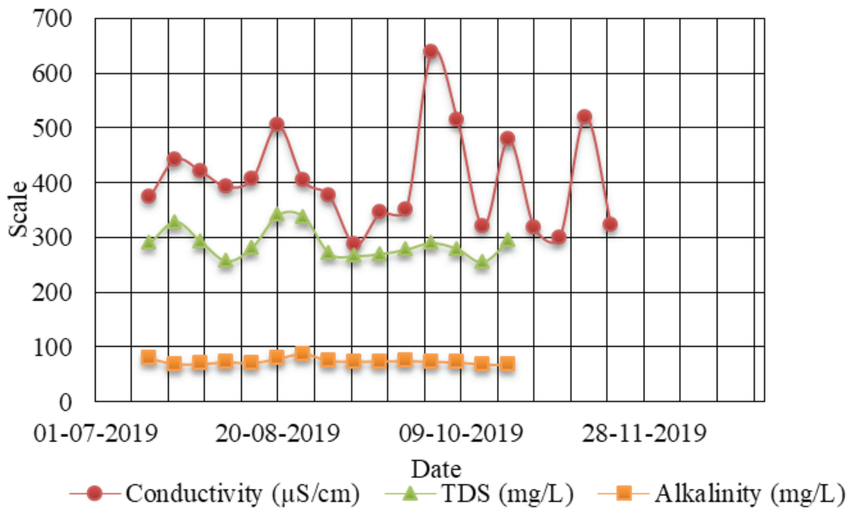

Figure 10 : Conductivity, TDS and alkalinity monitoring.

3. CONCLUSIONS

An extensive characterization program has been applied to seek compatibility in terms of stresses and strain, between the cutoff walls built in the upper part of the Ituango dam and surrounding rockfill zones, filter and core. This program has included tests of unconfined compressive strength, estimation of elastic modulus, permeability, dispersion with pinhole test, CU triaxial, flexural strength and permeability after an axial strain of 2%. Additionally, the characterization has been contemplated with field tests such as Lefranc, to verify in situ hydraulic conductivity/permeability. The findings of this study are useful as input data of numerical analyses in static, dynamic and seep conditions (tools used in the estimation of the operation conditions of the barriers).

Since remaining seepage continues to appear, also a post-construction chemistry monitoring was applied. Records include pH, temperature, alkalinity, total dissolved solids and electrical conductivity of the seepage and the water reservoir. This procedure was used to follow variables associated with a potential internal erosion, probably caused by excessive cracking of the cutoff, which is undesirable for the operation of Ituango Dam.

REFERENCES

Consorcio CCC Ituango. (2019). *CI-11718 Resultados ensayos de laboratorio con corte de 22 de febrero de 2019 al 03 de marzo de 2019*. Informe de control de obra, Ituango, Antioquia.

Consorcio Ingetec Sedic. (2019a). *INT-OC-EPM-189/19 Hallazgos perforaciones extensómetros EM4, EM5, EM6, EM7*. Informe de Interventoría, El Valle de Toledo, Antioquia.

Consorcio Ingetec Sedic. (2019b). *PHI-IFF-LC1-024-R1 Informe final de obras principales parte 10- construcción en la presa de la pantalla cortaflujo en lechada plástica*. Informe de Interventoría, El Valle de Toledo, Antioquia.

Consorcio Ingetec Sedic. (2019c). *PHI-IND-LC1-CCCI-2366*. Informe de avance diario, El Valle de Toledo, Antioquia.

Dam Safety Technology Development Program. (2005). *Report DSO-05-03 Seepage Chemistry Manual*. Denver Colorado: Bureau Reclamation -U.S. Department of the Interior.

Integral Ingenieros Consultores. (2019). *I-2194-Estabilidad global presa contingencia (Actualización a diciembre 2019)*. Informe de diseño, Medellín.