A Brief Analysis of the Leaching Process in the Backfill Concrete of a Powerhouse

Claudio Neumann Junior, Ana Carolina Parapinski Dos Santos and Etore Funchal de Faria

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BRIEF ANALYSIS OF THE LEACHING PROCESS IN THE BACKFILL CONCRETE OF A POWERHOUSE

Cláudio Neumann Junior[*], Ana Carolina P. Santos[†], Étore F. de Faria[‡]

[*]Itaipu Binacional / UNILA – Universidade Federal da Integração Latino-Americana
Avenida Tancredo Neves, 6731 – Foz do Iguaçu – PR, Brasil
e-mail: neumann@itaipu.gov.br, webpage: www.itaipu.gov.br

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Abstract. *The long-term behavior of concrete is an important topic where critical infrastructure projects are concerned. Deterioration of concrete structures subjected to aggressive water is often characterized by the leaching process that occurs gradually in structures in long-term contact with water. Leaching or lime-leaching refers to CaO (in reality Ca^{2+} and OH^{-}) being removed from the concrete by dissolution in water. Leaching enlarges the pore system of the concrete temporarily increasing the permeability, although dissolved ions may later precipitate inside the pore system, reducing the permeability of the parts involved. Some variables are involved to a greater or lesser degree in such an event, such as hydrostatic pressure or environmental conditions. This study aims to advance research related to the leaching process in the foundation concrete of the Itaipu hydroelectric powerhouse. Previous analysis carried out up to 1993 indicated that there were no risks to the stability of this structure, which could negatively impact the operation of the electromechanical equipment, this being the reason why these analyzes have been partially discontinued since then. Although the instrumentation demonstrates satisfactory behavior of this section, there have been no specific studies regarding the recent characteristics of this section's concrete. Chemical analyzes of infiltration water have been performed in laboratory, which results make possible the cognizance of the intensity of existing leaching and its kinetics, so that preventive and corrective actions might be adopted, if necessary, with the purpose of extending the useful lifespan of this undertaking.*

1 INTRODUCTION

Concrete is a reactive porous material and has hydrates and water as the main components. Its solid phases are in thermodynamic equilibrium with the chemical solutions inside of the surrounding pores, with calcium being the main chemical element of the cement paste [1].

Cementitious materials are widely applied in structures such as chemical industries, nuclear power plants, dams, ports, bridges, tunnels, pipelines, water reservoirs and other submerged constructions. Because they have continuous contact with water, they are easily corroded by it, and structural performance reduction occurs [2-5].

[†] UNILA – Universidade Federal da Integração Latino-Americana
[‡] Itaipu Binacional

Degradation due to calcium leaching has been reported since the 1920s. Despite this, there are few cases in which simple structures have been damaged by this process, since the rate of degradation is relatively slow [6].

Alterations in the cement paste caused by dissolution are not usually a matter of interest for concrete works in general. However, in special concrete structures, the phenomenon of leaching becomes important [7].

In order to guarantee long life of hydraulic structures, a better understanding of the effects of natural waters on the deterioration of concrete is required [5, 8].

2 THEORETICAL REFERENCES

2.1 General definitions of leaching

Calcium leaching is a process of chemical degradation [1], whereby there is mass transport from a solid to a liquid [9], depending on the differences in composition and concentration between the water in contact with concrete and the internal solution of their pores [1, 4, 8, 10].

The most vulnerable components of the paste to dissolution are portlandite (calcium hydroxide, Ca(OH)2) and calcite (calcium carbonate (CaCO3)) [11]. The concentration of the pore solution is decreased, and finally the solid calcium of the structure gradually dissolves [2, 10].

2.2 Decalcifying agents

Cement-based materials like paste, mortar and concrete are subject to leaching when in contact with constantly renewed liquids such as pure, distilled, deionized, sweet or desalinated water, who acts as solvents [2, 4, 8, 9].

Calcium hydroxide (Ca(OH)2) can be leached by long-term water flows [4], but the concrete performance also depends on the chemical environment where it is exposed [3].

Under natural conditions, although the progress of the leaching front has velocity of a few millimeters in hundreds of years, it is considered one of the most important processes of concrete degradation in the long term, especially if in aggressive environments where the combination with the chemical attack may be even more critical [5].

2.3 Effects on porosity, density and absorption

Many researchers have reported the cementitious materials performance against leaching, noting that there is an increase in porosity of the cement paste over time [1, 4, 5, 7, 11, 12]. As the microstructure changes, the permeability increases and the mass density decreases [2-5, 7, 11].

In the process of calcium leaching, pores or porosity play a very important role. First, the dissolution and diffusion of the calcium ions occur in the solution inside the pores. Subsequently, the dissolution of the calcium of the structure will generate new pores in the space. Further, this new increase in porosity will result in a higher diffusion coefficient or permeability, which will further accelerate the leaching process, in a progressive effect [3, 10].

Exposure to long-term leaching can significantly alter surface concrete [8], which leads to a reduction of the concrete's protective effect on steel bars [2], as a function of pH decrease, inducing corrosion of reinforcement [5].

2.4 Effects on mechanical properties

Leaching caused by fresh water is one of the most significant factors related to Portland cement-based pastes, mortars and concretes durability [3, 4].

This phenomenon leads to the degradation of the mechanical properties of the material [1-4, 9, 11]. It is possible to observe the stress-strain diagrams who illustrate the significant reduction on the material stiffness [12].

The impact of calcium leaching on the dimensional stability of concrete works requires new approaches to the design and operation of critical structures to ensure the integrity of the material and structure for long periods of time [13].

2.5 Evaluation through microscopic tests

Microscopic methods have been used to evaluate the material composition and microstructural morphology of cement pastes subjected to leaching, such as scanning electron microscopy (SEM)[2-4,8-10], spectrometry[3], diffraction of X-ray (XRD)[2,4,8] and thermogravimetry [8].

However, since SEM only deals with surface aspects, it is still very difficult to obtain the spatial distribution of porosity. Thus, another feature is computed tomography, which allows internal observation in three dimensions of the sample pores with no need of special preparations of it [10].

2.6 Prediction through mathematical models

Due to the complexity of long-term experiments, most researchers tend to use mathematical models based on the amount of ions, leaching depth, diffusion coefficient and other kinetic parameters to predict the behavior of hardened pastes in relation to leaching [4].

Mathematical models can provide predictions of residual resistance and estimated useful life of structures subject to environmental aggressiveness, although the extent of their validity in structural simulations still depend on better exploitation of knowledge [1].

Some long-term forecasting techniques were constructed by YANG *et al* [3], whose results were compared with actual concrete values existing 30 years ago, obtaining a good correlation.

Nevertheless, the influence of the element size can not be well evaluated, since the extrapolation of data through computational experiments for large structures is delicate, due to the fact that accuracy is lost as the structures under study are larger [1].

2.7 Accelerated tests

Considering that leaching in natural environment is very slow, some accelerated experimental procedures have been carried out [2,5,9], including the use of small sample sizes, large volumes or frequent leach fluid exchanges and high temperatures [9]. These tests are necessary to calibrate mathematical models and validate them [1].

Other methodologies consider the use of chemical solutions such as ammonium nitrate [1-3, 5, 11-13] or ammonium chloride [3]. There are also processes with electric fields application, use of deionized water and tests under flow conditions [5].

2.8 Some studies around the world

Leaching has been extensively studied in the last two decades [10] and many researchers have discussed the physical and mechanical properties of cementitious materials subject to leaching [3] or long term damage caused by natural water attack [11].

Despite this, the relationship between the mechanical properties and the duration of the process has been rarely quantified in the literature [3]. There is also limited data comparing the physical and microstructural properties of cement mortars pre and post-leaching [4,5,7,9].

One of the rare real-time experiments cited in the literature was carried out by TRAGARDH and LAGERBLAD [14], in which several samples of concrete from a reservoir that underwent water attack during 90 years were analyzed, having been observed an increase of the porosity resulting from the dissolution of the phases of the within a degradation zone of approximately 9 mm in thickness.

Leaching degradation was also observed in a few cases of hydroelectric power plants or projects related to water supply after long periods of operation of approximately 100 years [6].

Another study was developed by ROSENGVIST *et al* [8] and discussed the mechanisms of change in a concrete exposed for 55 years to the water of the Ångermanälven river, in the north of Sweden. It was observed that calcium components leaching significantly increases the harmful effects of freezing and abrasion in the deterioration rate of the surface.

However, further investigations are necessary to establish other effects such as water composition (hardness and pH), or whether it is current or stationary [11].

2.9 Results obtained in the literature

Initial evaluation procedures usually involve the application of phenolphthalein solution to surfaces to identify the depth of Ca(OH)2 leaching [11]. Its pink to violet color corresponds to high pH, higher than 9.5, by the presence of calcium hydroxide, whereas areas without this color are those where leaching has already occurred [8, 11].

There is also mention of the beneficial effects of fine particles of pozzolanic silica on leaching and consequent deterioration [11], whereas for the results of the analysis of samples with incorporation of appropriate amount of slag showed low rate of microstructural deterioration and good resistance to leaching , when compared to samples without slag [2, 4].

Regarding to the water / cement factor (a / c), it was observed [2,3] that exists proportional relationship between porosity and a / c factor. The models with low a / c ratio [6] also showed greater resistance to leaching.

There is a linear relationship between the depth of attack (distance from the sample surface to the dissolution front) and the square root of time [7, 11], although the leaching depth still strongly depends on the cement type, the material compactness, the aggregates presence and also the chemical characteristics of the surrounding environment [3, 11] and temperature [3, 6], since this one increases the diffusion rate.

Chemical and mineralogical characterization of concrete samples from different points of the structure under study can also provide information on the effects of leaching and hydrostatic pressure on cement paste change [8].

3 MATERIALS AND METHODS

3.1 General data of Itaipu power plant

Itaipu Hydroelectric power plant is a binational entity located at Paraná River, on the border between Brazil and Paraguay (Figure 1), built between 1975 and 1982 by both countries. It has 20 generators, 16 of them in the power house of the main bed of the river and 4 others in the Diversion Channel. With 14,000 MW of installed power, it supplies about 15% of the energy consumed in Brazil and 75% of that consumed in Paraguay.

Figure 1: General view of Itaipu power plant.

The dam is approximate 7,700 m long and has a maximum height of 196 m. Its structure is composed by five kinds of dams: the rockfill dam, formed by a core of compacted clay, lined with rock blocks from the Diversion Channel excavations; the earth dam made of clay from the excavations of the rockfill foundation and its neighbor areas; and concrete of the hollow gravity, gravity dam and buttress dam.

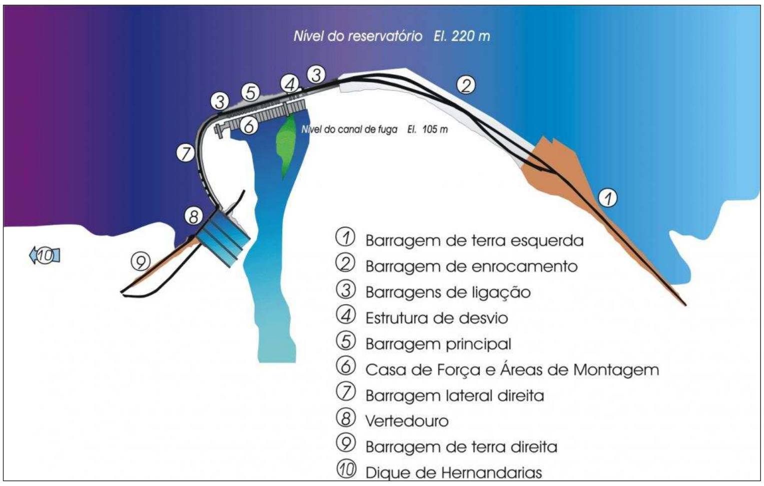

Figure 2: Itaipu complex plant.

3.2 The backfill concrete

For the powerhouse construction, alluvial material from the river bed was excavated between Elevations 39 and 54. Backfill concrete was replaced in this region, which corresponds to the units U-6 to U-10, in an approximate volume of 150,000 m^3.

Roller compacted concrete (RCC) was specified for this site, with 10 MPa compressive strength at 365 days, and aggregates up to 152 mm diameter. Continuous layers of 50 centimeters thickness were poured by off-road trucks, spread with tractors and compacted by vibrators coupled in bulldozers.

Later, while drilling the holes for the injection curtain downstream the powerhouse, which crosses the backfill concrete, it was observed that drilling water was lost, there was communication between holes up to 9 meters, with artesianism in neighboring holes and absorption of large volumes of cement grout from the injections.

This way, water loss tests were carried out on drilling holes in this region and about 40% of the cases showed permeability higher than 10^{-3} cm/s, similar to sand.

In the extracted samples, there were practically impermeable stretches, especially in the rock-concrete contact and on the surface of the El. 54, with a thickness of approximately 50 cm. Some other zones of lower porosity interspersed with other more permeable ones were identified, which would probably correspond to the sites of greater water absorption and cement grout.

This problem, together with the impossibility of determining the real extent of the affected regions, has raised concerns about the possibility of excessive repression and deformations which could affect the stability of civil structures and consequently the positioning of electromechanical equipment; the increase of the subpressions due to more percolation that would overload the drainage system; and the decrease in concrete durability due to the leaching.

Providences included some interventions:

- two drainage curtains were executed on the left and right sides of the backfill concrete, capturing infiltration waters of the shoulders and leading them to the drainage tunnel at El. 20, thus preventing these waters from penetrating the concrete;
- injection curtain executing at downstream gallery on El. 60, along downstream face of the backfill concrete, in order to prevent water percolation through the concrete in downstream-upstream direction. This curtain was composed by three injection fronts: the central one with epoxy resin and the others with cement mix;
- installation of two extensometers in the backfill concrete to accompany its deformations;
- qualitative and quantitative analysis of the percolation waters, to evaluate the leaching process.

Upon completion of the downstream injection curtain, a noticeable reduction of about 100 times in the concrete's permeability was observed. It was also observed a tendency of uniformity of the permeability of the concrete, through the tests of water loss.

4 PARTIAL RESULTS AND DISCUSSIONS

4.1 Instrumentation analysis

It can be observed in Figure 3 that the extensometers have a seasonal behavior, with maximum values in the order of 0.3 mm and currently oscillating around 0.05 mm in EM-U-021; and trend of continuous settlement in EM-U-022, which shows present values close to 1.4 mm.

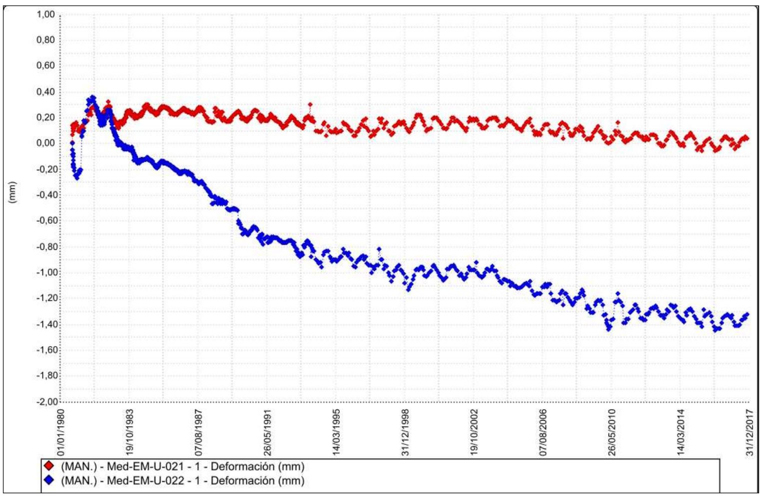

Figure 3: Extensometers in the backfill concrete.

It is important to compare these extensometers with others of the same region, according to Figure 4, which also shows a small tendency of settlement, with current values of about 6.7 (EM-U-013) to 8.2 mm (EM-U-014) in the foundation rock, within the project estimates.

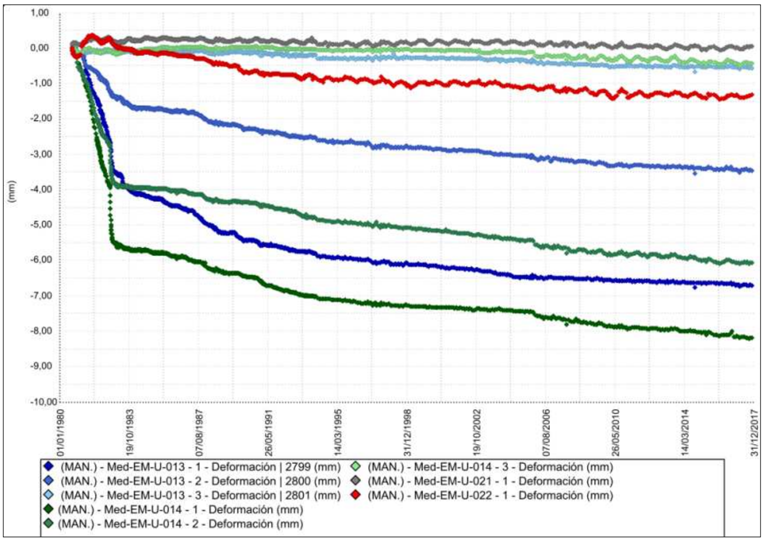

Figure 4: Extensometers in the backfill concrete and in the foundation rock.

4.2 Water analysis

Regarding to chemical tests of percolation water, carried out from 1984 to the present, it is observed that occurs a reduction in carbonate contents (Figure 5) and an increase in bicarbonates (Figure 6), especially since 2008; and from 1991, the absence of hydroxide (Figure 7) and the reduction of calcium (Figure 8), the latter being more noticeable in relation to DTJ-U-008 and 012 drains.

There is also a small increase in flow rates in DTJ-U-004 and 008 drains, while DTJ-U-012 flow rates practically stabilized, according to Figure 9.

There is no information about chemical tests performed between 1994 and 2003, as well as flow data between 2003 and 2013.

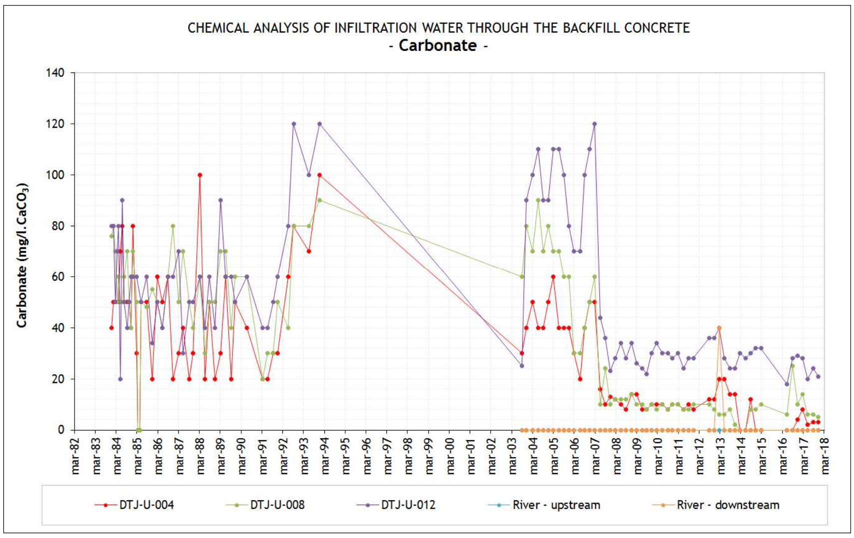

Figure 5: Carbonate contents.

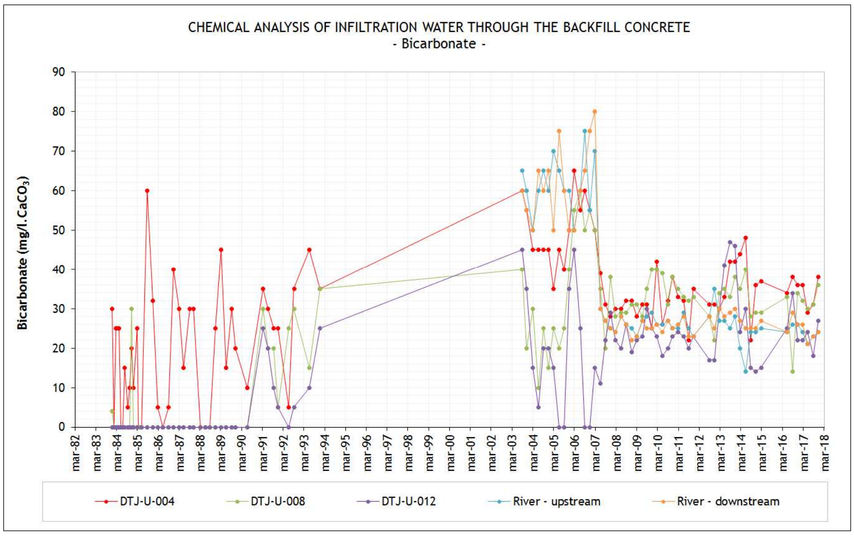

Figure 6: Bicarbonate contents.

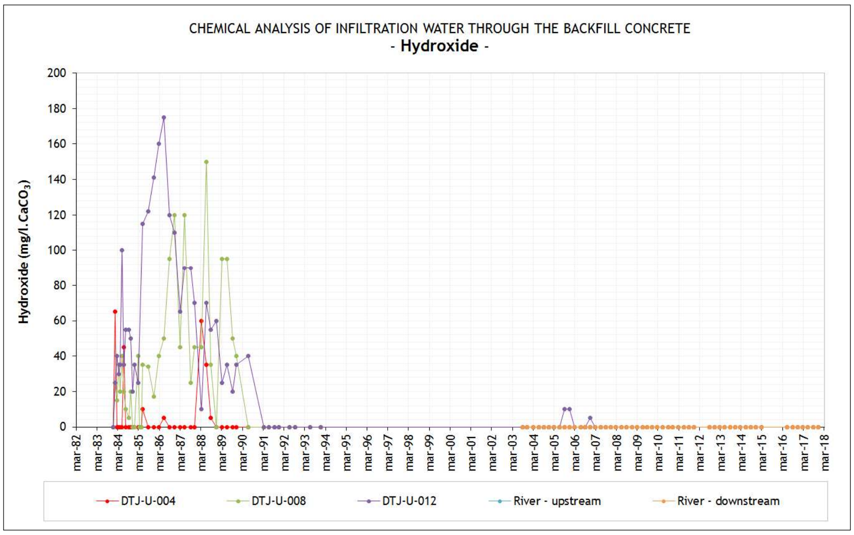

Figure: Hydroxide contents.

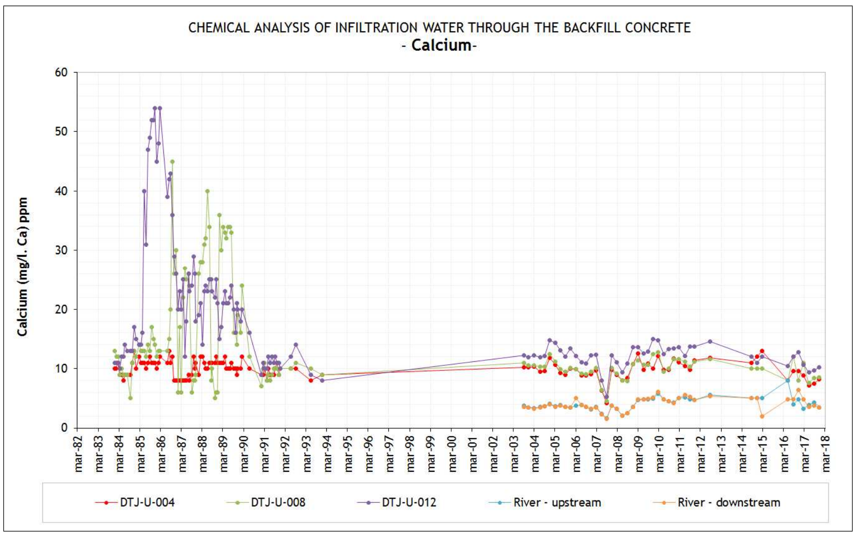

Figure 8: Calcium contents.

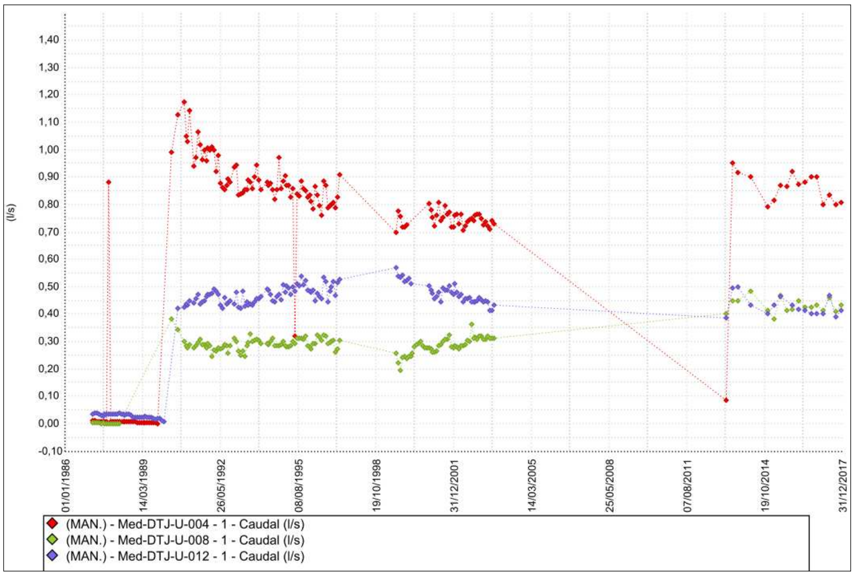

Figure 9: Infiltrations through the backfill concrete.

Although there are other drains in this region, these three ones are considered the most important because they correspond to about 90% of total water infiltrations through there.

5 CONCLUSIONS

Considering the instrumentation behavior and the results of water chemical analyzes, it is understood that the leaching process on the backfill concrete, although still occurring, is stabilized.

An earlier study estimated the approximate time of 140 years for the admissible loss of 20% of the concrete's calcium, under certain assumptions, representing no risks of structural impairment. In subsequent stages of the current research it is intended to reproduce the leaching process at laboratory for a new evaluation of its long-term effects.

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