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Evaluation of Interference of Iron Bacteria in Geotechnical Works in the State of Ceara-Brazil

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Abstract. Iron bacterias use elements such as iron, through oxidation and reduction processes. As a product, the ochre: a gelatinous slime material, rich in iron, with adhesive properties. The crystallization make this slime a problem for civil engineering, once it fills and obstructs drainage systems. This study proposes the analyze of the interference of iron bacteria in geotechnical works in the State of Ceara, through the correlation among the ideal conditions to their development, mapping regions with the presence of mineral iron in their subsoil, as well as water quality parameters of dams reservoirs. It was observed that all the reservoirs indicated an ideal environment for the growth of iron bacterias, including the Jaburu I Dam, where a sediment sample was also collected for tests, revealing the presence of ochre.

Keywords. Dams, Geothecnical Works, Iron Bacteria, Ochre.

1. Introduction

Iron bacteria, different from the others, are a group of aerobic and autotrophic bacteria that perform a process of chemosynthesis through the oxidation of manganese, aluminum and mainly iron ions dissolved in water, which are indispensable for their metabolic activities [1].

There are some peculiar and adequate conditions for an efficient proliferation of these microorganisms, as explained by Menezes [2], in which rainy periods contribute positively to the life of these bacteria, as well as the significant presence of iron in the soil and/or dissolved in the water. These bacteria develop better at the interface of aerated and non-aerated environments, in which sandy and lateritic soils have been shown to be more propitious for their proliferation, as well as groundwater, since they generally have a higher concentration of dissolved iron [3].

In these soils, the result of the chemical reactions between the iron bacteria and the elements previously mentioned, is a gelatinous ferrous material are formed by these microorganisms, the ochre [4]. This material, over time, goes through processes of aging and crystallization, damaging hydraulic and geotechnical systems and structures, since they offer a more inviting environment to their appearance and metabolism.

In drainage ducts, for example, the presence of these bacteria is characterized by water with orange coloration and strong characteristic odor, due to the high concentration

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of iron, as well obstructions of the equipment as consequence of the ochre already crystallized inside the pipe [3]. In geotextile filters, the situation doesn't differ, since one of the causes of clogging, as explains Mendonça [5], is also the product of chemical-microbiological activities of the iron bacteria, resulting in a decrease of filtering capacity, as well as a lack of essential requirements such as drainage efficiency, retention power and service life.

The State of Ceara has a subsoil that contributes potentially to the life and reproduction of the iron bacteria, considering that it is constituted, for the most part by crystalline rocks covered by thin layers of residual soil, as shown by Gomes [6], in which the mantle is divided into two sublayers: the superficial layer, characterized by being sandy or lateritic, and the deeper layer, generally referred to as saprolite. Therefore, sandy soils, having as main characteristics a granular composition and a great porosity provide a favorable environment for these bacteria, since the voids in this type of soil are easily filled with oxygen, being this essential element for their metabolisms, making possible as they spend less energy [5], as well as allowing greater circulation of water.

On the other hand, the lateritic and saprolithic soils, because of the concentration of ferric oxide in their composition which gives them a reddish coloration, provide the necessary amount of iron for the iron bacteria, and the production of ochre.

2. Life cycle of iron bacteria and ochre

Iron bacteria are aerobic microorganisms widely distributed in the environment, especially in soils, groundwater, wells and water from drainage systems. These bacteria differentiate by precipitating relevant quantities of iron oxides and hydroxides in the water, forming flocs, the ochre [2].

Sphaerotillus, Leptothrix, Crenothrix and Gallionella are the most frequent types of iron bacteria that cause complications when present in the water. They are distinguished by the filamentous arrangement of their cells, which are enveloped by a helical sheath perpendicular to the axis of the cell and, therefore, are also referred to as sheath bacteria [7], as can be seen in Figure 1.

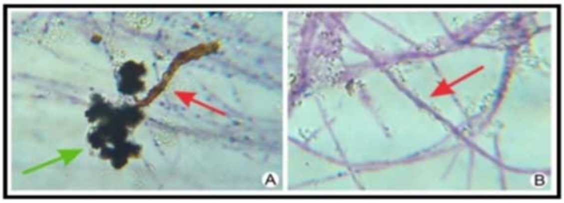

Figure 1. Micromorphology of Iron Bacteria (GRAM staining).

They are unicellular and secrete a filamentous structure, organized in the form of interlaced ribbons, in which, from the oxide or iron hydroxide deposited in the cell, they are diluted into strong acids. Soon after, the detachment occurs, the amount of suspended solids in the water increases. In the presence of oxygen, these bacteria oxidize the ferric ion (Fe2 +) to ferric ion (Fe3 +), releasing energy and depositing ferric hydroxide (Fe (OH) 3) brown-orange and insoluble [8].

One of the differentials of the iron bacteria in relation to the others is in the peculiar and adequate conditions for an effective proliferation, as explained by Menezes [2], which rainy periods contribute positively to the life of these bacteria, as well as the significant presence of iron in the soil and/or in water. Given these circumstances, some habitats are more attractive to the growth of iron bacteria, as shown in Table 1.

Table 1. Variety of habitats in which the main genera of iron bacteria occur.

Genus	Habitat				
	Soil	Fresh Water	Swamps	Mud in lakes and rivers	Wells and channeled systems
Sphaerotilus	-	+	-	+	+
Leptothrix	-	+	-	+	+
Gallionella	+	+	+	+	+
Crenothrix	-	+	-	-	+

2.1. Factors influencing the growth of iron bacteria

It is important to know the chemical and physical aspects of the environment that influence the development of the iron bacteria, discussed individually by Cullimore [4] and van Veen, Mulder and Deinema [9]:

- **Iron:** plays a crucial role in bacterial growth. Tests show that, under static water conditions, iron bacteria of the genus Gallionella and Leptothrix grew adequately with iron concentration varying between 1.6 and 12 mg / L [4];
- **pH:** according to Cullimore [4], better development in media with pH ranging between 5.4 and 7.2; however, Van Veen, Mulder and Deinema [9] show that the range of variation suitable would be around 6.5 to 8.1;
- **Oxygen:** bacterias need oxygen to live and perform their microbial activities. Thus, presence of oxygen contributes positively to their proliferation [9];
- **Temperature:** Sphaerotillus and Leptothrix, generally grow at temperatures between 15 and 40°C, with the ideal being at about 30°C;
- **Carbon:** Gallionella are the ones that need carbon as a requirement for their activities.

2.2. Characterization of ochre

Ochre is a gelatinous extracellular material, rich in iron and colors ranging from reddish to brown. Gameda [10] states that this biopolymer mass has a large viscous and adhesive character. As soon as deposited by iron bacteria, the ochre represents a biofilm of the same set of microorganisms wrapped in the compound of organic polymeric matrix that they themselves excrete and precipitate, in general, in inert surfaces. Over time, this mass increases in volume, causing crusts and with aging and dehydration, crystallizes and takes mechanical resistance and insoluble in water [3].

Studies conducted in the United States determined relationship between soil types and ochre accumulation in buried structures. According to Hamon [11], soil types that show a greater potential for ochre formation are fine and silty sands, organic soils, soils with high iron content. The soils less probable to the risk of formation and accumulation of ochre are silty clay soils and pure clays, because they are poor in ferrous iron [11].

2.3. Examples of Ochre in some geotechnical and hydraulic systems

Geotextile filters are composed of thin, permeable and flexible synthetic blankets, in which the main materials are polymers, such as polyethylene, polyamide (nylon), polyester and polypropylene [5]. Mendonça et al. [12] tested three types of geotextiles, in order to analyze the deposition of ochre biofilm in each case, in a controlled environment to the concentrations of iron, oxygen and pH, resulting in Figure 2.

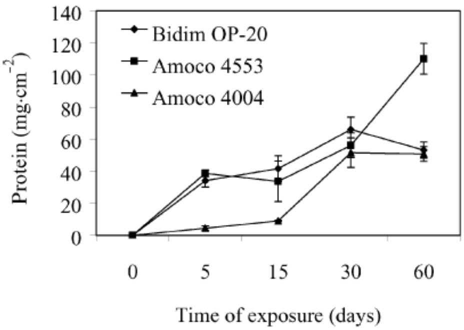

Figure 2. Relation between types of geotextiles and the formation of ochre.

With the action of iron bacteria in these systems, the ochre produced can trigger the process of filter filling.

In Drainage ducts the presence of the iron bacteria is characterized by water with orange coloration and strong characteristic odor, due to the high concentration of iron, causing possible obstructions in equipment, as a consequence of the aging and crystallization process of the ochre inside the pipe, as seen in Figure 3 [3].

Figure 3. Duct clogging due to ochre accumulation.

In earth dams, gelatinous materials from iron bacteria can be easily found in flow meters and water outlets, as they allow a circulation of nutrients, as well as greater amount of oxygen [13]. Silveira et al. [14] reports the appearance of ochre deposition in Castro Alves Hydroelectric Power Plant, located in Rio Grande do Sul- Brazil, found mainly in drains, enhancing the possibility of incrustations in pipes, associated with cracks and joints between blocks of the structure, with infiltrations.

3. Studies performed

In this work, a comparative evaluation was carried out between studies about the deposition of ochre and geotechnical works of the State of Ceara, in regions with significant concentrations of iron, both in soil and in water, also taking into account other parameters, such as pH and temperature. Soon after, a documentary research done in which the regions with the presence of the iron of its subsoil are noticed, through maps of the geodiversity of Ceara. Then, dams located in these areas were selected and information about water quality was taken - pH, temperature and iron concentration.

Subsequently, a sample of material from the upstream flow measurement box in the Jaburu I Dam (located on the border of the municipalities of Ubajara and Tiagua) was collected in order to be analyzed in laboratory. The following tests were performed:

- X-ray diffraction (XRD) with subsequent computational treatment of the phases obtained through the Rietveld method.
- Thermal Analysis (Thermogravimetry - TG and its derivative - DTG) obtaining the mass loss temperatures of the organic constituents.

The results obtained for the X-ray diffraction were lauded by the laboratory technician responsible, based on the studies of Chovan [15] and Tuhela et al. [16].

In order to parameterize the data to be used for the comparison with the results, Table 2 summarizes the ideal conditions for development of the microbial activities of the iron bacteria.

Table 2. Ideal water quality parameters for the development of iron bacteria.

Iron Bacteria	Water		
PARAMETERS	pH	Temperature	Iron concentration
	6,5 to 8,1	15 to 40 ºC	1,6 to 12 mg/L (water without flow) minimum 0,2 to 0,5 mg/L (water with flow)

4. Analysis of results

4.1. Water and soil

Based on documentary data of the geodiversity of Ceara and on the map of the areas of relevant mineral interest, shown in Figure 4, it can be observed the presence of iron in three regions of the state: Sobral - Camocim, Novo Oriente - Taua and Campos Sales - Antonina do Norte. In addition, the fact that the state that has layers of lateritic soils, with predominance of hydroxides and hydrated iron oxides in its composition, points that there is a certain potential for the proliferation of iron bacteria in their lower layers.

For the reservoirs located in the regions previously mentioned, were selected to study the parameters, such as pH, temperature and iron concentration. The Premuoca, Varzea da Volta, Jenipapo, Martinopoles e Angicos reservoirs were select for the Sobral - Camocim region. The Trici Reservoir was select in the region of Campos Sales - Antonina do Norte and, in the region of Novo Oriente - Taua, it was select the Poço da Pedra reservoir. The parameters of pH, temperature and iron concentration of the chosen reservoirs were provided by the Water Resources Management Company (COGERH), with water quality analyzes corresponding from the year 2008 to the year 2018. These data were treated statistically for each parameter, in order to represent the interval of 10 years of collection, as well as the amplitude of the values for iron concentrations, resulting in Table 3.

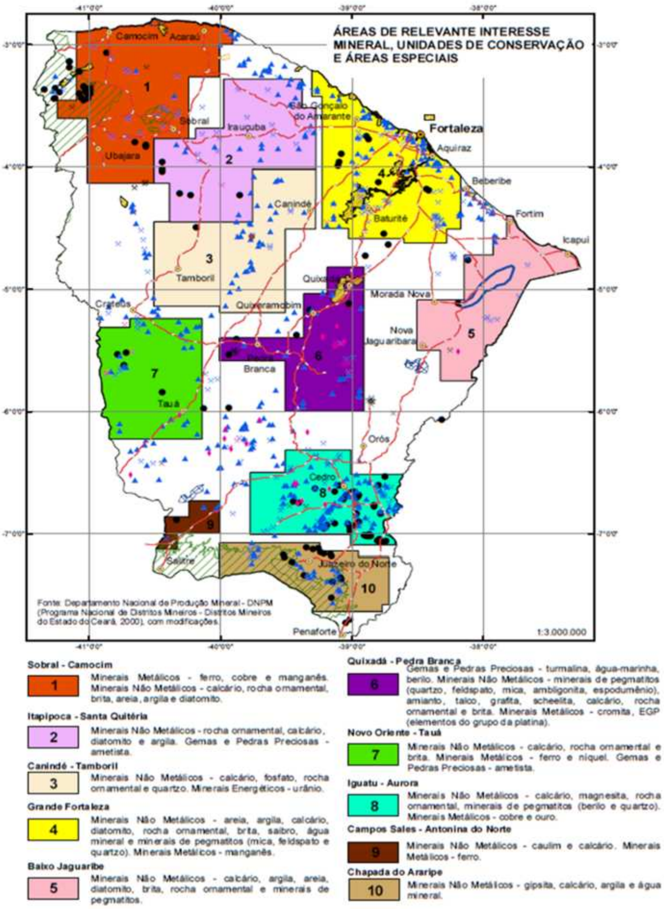

Figure 4. Map of areas of mineral interest, conservation units and special areas.

Table 3. Average water quality parameters of the reservoirs selected in the survey.

REGION	Reservoir	pH	Temperature	Iron Concentration	Amplitude
Sobral – Camocim	Premuoca	7,94	29,7 °C	0,45 mg/L Fe	0,25 to 0,81 mg/L Fe
	Varzea da Volta	7,94	29,9 °C	0,44 mg/L Fe	0,21 to 1,83 mg/L Fe
	Jenipapo	7,65	26,21 °C	0,32 mg/L Fe	0,22 to 0,67 mg/L Fe
	Martinopole	7,6	29,44 °C	0,80 mg/L Fe	0,31 to 1,51 mg/L Fe
	Angicos	8,1	29,21 °C	0,32 mg/L Fe	0,21 to 0,47 mg/L Fe
Novo Oriente – Taua	Trici	8,17	26,68 °C	0,96 mg/L Fe	0,22 to 3,42 mg/L Fe
Campos Sales – Antonina do Norte	Poço da Pedra	8,6	27,82 °C	0,73 mg/L Fe	0,23 to 1,83 mg/L Fe

Most of the reservoirs present the ideal pH range to the grown of iron bacteria (6.5 to 8.1), pointed for van Veen et al. [9], with the exception of the Poço da Pedra Dam. The water temperature averages are all within the range (15 to 40 ° C). In relation to the iron concentrations, all reservoirs have the minimum or higher amounts for the development of the iron bacteria, compared to Table 2. The lower and upper extreme values for iron concentrations, point out that the reservoirs of Varzea da Volta, Martinopole, Trici and Poço da Pedra are more susceptible to ochre, according to Cullimore [4].

4.2. Characterization of water and sample material - illustrative case: Jaburu I Dam

Jaburu I Dam was built in 1983, with compacted lateritic soil and as an internal drainage system, filter and sand drains. Historically, in 1997 some wet areas were detected on the downstream slope, raising a probable inefficiency of the internal drainage system at that time. The water was described with a rusty appearance with deposition of reddish colloidal material and corrective measures were adopted. In 2003, there was a new appearance of water in the downstream slope and again the collected water had a rusty appearance as well as the sedimented material in the flow meter box installed downstream of the embankment had a colloidal appearance. At present time, the piezometric levels in the downstream slope presents significant readings, suggesting the existence of percolation outside the filter, again indicating strong signs of problems in the drainage system. In addition, percolated water exhibits the ferruginous characteristics and deposition of reddish colloidal material. For the present study, material deposited on the flowmeter was collected, which was taken to the laboratory.

4.2.1. Reservoir water

As well as the other reservoirs studied, pH, temperature and iron parameters of the Jaburu I Dam were provided by COGERH were analyzed, resulting in Table 4.

Table 4. Average water quality parameters of Jaburu I Dam.

Resorvoir	pH	Iron Concentration	Amplitude
Jaburu I	7,62	25,2 °C	0,31 mg/L Fe

According to the results presented, the average obtained for the pH is within the ideal range for the appearance of the iron bacteria (6.5 to 8.1), as well as the average water temperature of the reservoir, since the ideal range is between 15 and 40° C. In relation to the iron concentration, it can be observed that it has the quantity of iron in the water superior to the minimum necessary for the development of the iron bacteria.

4.2.2. Material

The sample collected at Jaburu I Dam (Figure 5 - left) showed reddish brown coloration, with viscous gelatinous appearance and ferruginous appearance, characteristics that are in agreement with the ochre aspects described in Gameda [10] and Mendonça [12].

Figure 5. Sample from Jaburu I Dam (left) and the same after drying process and maceration (right).

- X-Ray Diffraction (XRD): The X-ray diffraction test was performed with the objective of identifying the crystalline phases of the material.

For the sample (Figure 5 - right), the diffractogram shown in Figure 6, presented a non-flat region, typical behavior of amorphous samples with absence of crystallinity. It is suggested that this lack of crystallinity may be the result of a strong presence of organic matter, both from the environment and from the origin of bacterial metabolism.

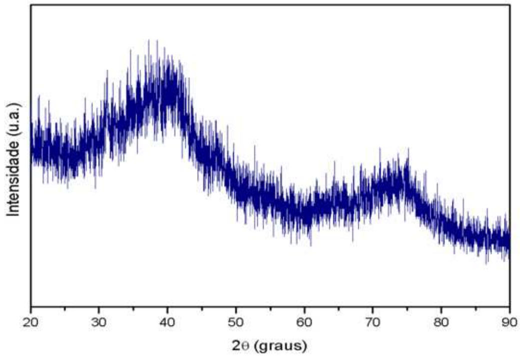

Figure 6. Diffractogram obtained for sample collected at Jaburu I Dam.

Comparing the diffractogram obtained for the sample with the results obtained by Chovan et al. [15], it can be concluded that the sample collected is ferriidrite, a poorly ordered Fe (III) oxide of the volumetric formula 5Fe2O3.9H2O, or ochre. The results of Tuhela et al. [16] suggest that biologically catalyzed iron fouling of water wells begins with the initial formation of ferrihydrite. The observations made in relation to the sample, based on the obtained diffractogram, are also consistent with Ford [1] in their studies on the characterization of ochre, in which as well as relevant concentrations of iron oxides.

- Thermogravimetric Analysis (TGA) and its derivative (DTG): TGA is a method used to determine the thermal stability of a particular compound by changing its mass in relation to temperature. The thermogravimetric curve and its derivative, presented in Figure 7, confirm the presence of organic matter in the sample.

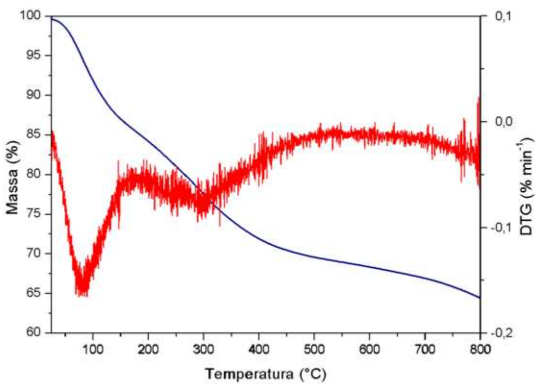

Figure 7. TGA (blue) and DTG (red) curves of the material from the Jaburu I Dam.

The sample had continuous mass loss during the whole heating process, especially the loss in the event between 25 ° C and 150 ° C, extended less intensely to 450 ° C, with a total mass loss of 36.08%. Although the sample was submitted to drying in oven, part of the mass loss can be attributed to the water remaining in the material, adsorbed on its surface and structural water, in addition to CO_2. However, the obtained curves are typical of samples rich in organic matter, probably extracellular polymeric substances produced by bacterial activity.

5. Conclusions

With the understanding of the life cycle of the iron bacteria, allied to the factors that influence its development, such as the presence of the mineral iron, pH, temperature, oxygen and carbon, as well as the characterization of ochre produced by these microorganisms, it was possible to evaluate their presence in geotechnical works. Through the results, the mapping made in the State of Ceara with potential regions for the appearance of the iron bacteria based on the amount of mineral iron in the subsoil was cross - referenced with information about water quality of some reservoirs within these areas with iron in the subsoil. As a result, the water from these reservoirs showed favorable conditions for the proliferation and maintenance of the life of iron bacteria.

Regarding the Jaburu Dam I - in addition to the water characteristics of its reservoir that showed a favorable way for iron bacteria - the results of the laboratory tests attested the presence of ochre denoting the direct action of iron bacteria. Based on this analysis, it can be pointed out that there are strong indications that correlate the deposition of colloidal material as well as ferruginous water produced by the iron bacteria with a possible consequence of the Jaburu I dam's filters clogging, and therefore denoting the interference of the iron bacteria in the system.

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