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Grain Size Effect on Durability of Bioclogging Treatment

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***Abstract*—**In this work, the bioclogging of two soils with different granulometries is presented. The durability of the clogging is also studied under cycles of hydraulic head and under cycles of desaturation-resaturation. The studied materials present continuous grain size distributions. The first one corresponding to the "material 1" presents grain sizes between 0.4 and 4mm. The second material called "material 2" is composed of grains with size varying between 1 and 10mm. The results show that clogging occurs very quickly after the injection of nutrition and an outlet flow near to 0 is observed. The critical hydraulic head is equal to 0.76 for "material 1", and 0.076 for "material 2". The durability tests show a good resistance to unclogging under cycles of hydraulic head and desaturation-resaturation for the "material 1". Indeed, the flow after the cycles is very low. In contrast, "material 2", shows a very bad resistance, especially under the hydraulic head cycles. The resistance under the cycles of desaturation-resaturation is better but an important increase of the flow is observed. The difference of behavior is due to the granulometry of the materials. Indeed, the large grain size contributes to the reduction of the efficiency of the bioclogging treatment in this material.

***Keywords*—**Bioclogging, Granulometry, permeability, nutrition.

I. INTRODUCTION

IN the last years, the use of bacteria became more and more important in many applications. Indeed, bacteria are used for example in the depollution of soils, in the reduction of the permeability of dikes, and dams, [1]-[4]. The bioclogging is defined as the combination of physical, chemical and biological processes [5].

This process consists in the stimulation of the bacteria of the soil by the injection of an adapted nutrient solution. So the increase of the biological activity of the bacteria results in the consolidation of the soil around the leaks after several weeks, to the reduction of the porosity and then to the permeability decrease [6]. The biological process presents three levels; the first level consists in increasing the biofilm covering the surface of grains. In the second level, the microorganisms grow as microcolonies called plugs. The third step is a macroscopic level, corresponding to the formation of a bulk [7]

Many works report that the permeability decrease varies as a function of the biological treatment and conditions. A reduction of about 22% of the permeability of a sandy soil is obtained by varying the amount of the produced polysaccharides [8]. A reduction by three orders of magnitude is observed by [9], associated to a reduction of 10% of the porosity. The results of a study carried out in columns on sandy soil are presented by [10]. The soil was inoculated with bacteria under a constant head difference between inflow and outflow. The results show a decrease of about 90% of the permeability and about 50–90% of the porosity. Similar tests were presented earlier by [11]. The authors suggest that the largest decrease of the permeability of sand, to the order of 79%, needs the addition of microrganisms during the filling of the columns. The results presented by [12] are also obtained with the injection of bacteria. The chosen bacteria present a rapid growth and good exopolymer rate production. They show that the permeability decrease presents three phases: the first one is quick and is due to the biomass accumulation; the second one is slow because the nutrition injection is stopped. In this case, the biofilm growth is due to the reserve consummation. The authors show that, in the third step, the biofilm and the permeability are stable even without nutrition injection.

The tests carried out with a percolation of columns with glucose solution of $50\mu g/cm^3$ for 120 days [13]. As observed in other studies, a quick decrease happens immediately after the injection, during the 10 first days. After this period, the permeability decrease is slower. The tests done by [14] show that, after 60 days, the permeability decrease is nearly one order of magnitude. The decrease is sharp at the beginning of the test and becomes slower at the end of the test.

Other works gives an interest to the study of the mechanisms accompanying the biological process. Indeed, [15] and [16] concluded, as a result of their tests performed in columns that the production of gas during the biological process can also contribute to the reduction of permeability of about an order of magnitude.

Many models try also to relate the reduction of the bacterial growth to the permeability reduction. There are some differences between the models as some of them consider that the permeability changes are related to biofilm growth and others to the growth of bacteria as colonies [17]-[19].

A model relating the biological mass growth to the hydraulic properties of the soil is also presented. The model

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concerns the growth of the biofilm as isolated colonies [20].

Many models show that, in the case of biological clogging, it is not possible to describe the relation between the permeability and the porosity with a relation like the Kozeny-Carman relation, but that the model must take into account the bacteria growth and the porosity evolution at the same time [21].

The effect of oxygen availability, sediment grain size and organic carbon (nutrient) concentration on the hydraulic properties of sand is presented. The sand is sieved at different grain size distributions (255–355, 355–500, and 500–710µm). The tests were carried out under aerobic and anaerobic conditions. Carbon at high concentration was injected. The results are better in the case of the anaerobic conditions. The authors also show that the grains size influences biclogging for a given concentration of carbon. For low carbon experiments, the bioclogging is not affected by the grain size. At a higher carbon concentration, the grain size plays a role in bioclogging [22].

Many works are centered on the effect of granulometry on bioclogging in many works [23], [24]. It appears that bioclogging is better in the case of fine materials. In the majority of the works cited in the literature review, the test materials were usually sandy soils or materials with homogenous grain size.

The aim of this work is to evaluate the effect of the grain size distribution on clogging. Two materials with different granulomerty curves were selected for this study. After the obtention of clogging, the durability of the clogged materials was tested by three tests (i) increasing the hydraulic head in order to determine the critical gradient corresponding to the destruction of the clogging, (ii) under cycles of hydraulic gradient and finally (iii) under cycles of desaturation-resaturation. The aim of these tests is to simulate the conditions in real dams.

II. MATERIAL AND EXPERIMENTAL TECHNIQUES

The materials used in this study are granular materials. The granulometry of these materials is presented in Fig. 1. The material with the finer grain size is called "material 1", the material with the coarser grain size is called "material 2".

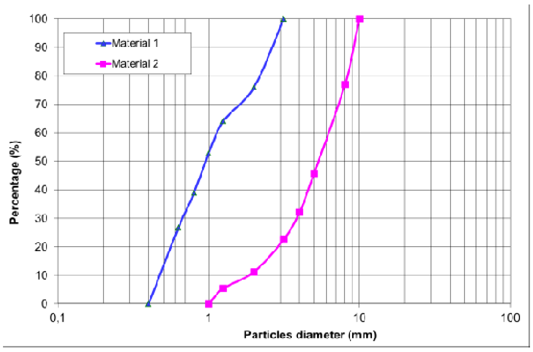

Fig. 1 Granulometry curves of the studied material

The columns parameters: The tests were performed in PVC columns with an inner diameter of 93mm and a length of 1 m (Fig. 2). The columns are equipped with 6 points for the water pressure measurement spaced of 15cm. The top and bottom piezometers, corresponding to the measurement points at 0 and 100 cm, are set at the contact between the specimen and the drain, made using the rule filter proposed by Terzaghi, and at the upper part of the soil respectively. The filter is made using the filter rule proposed by Terzagh. The water and the nutrition are injected from the bottom of the cell under a constant hydraulic head fixed since the beginning of the test to ensure a constant injection velocity. The constancy of the level of water in the inlet injection tank is ensured with a pump system. The injected water is tap water. The experimental device is presented in Fig. 2. The outlet liquid is collected and used to calculate the flow and the permeability of the soil before and after the nutrition injection.

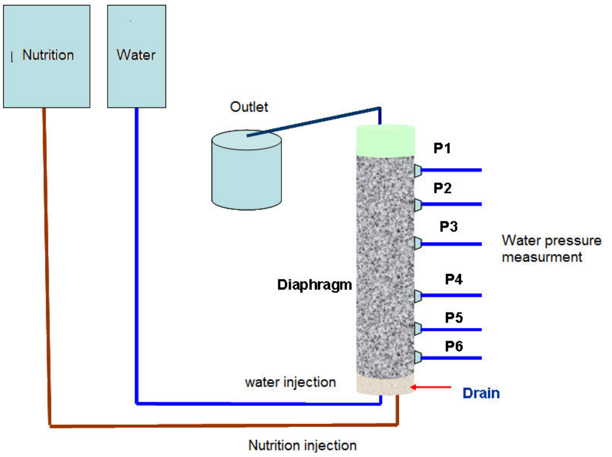

Fig. 2 Experimental device

The material characteristics: "material 1" presents a value of d_{10} equal to 0.4mm and a value of d_{60} equal to 1mm (Fig. 1). "material 2" presents a d_{10} and a d_{60} equal to 1.5 and 3mm, respectively. "material 1" and "material 2" present permeability values equal to 7.5 10^{-5} and 2.5 10^{-3}m/s, respectively. The characteristics of the materials are presented in Table I.

TABLE I
CHARACTERISTICS OF THE SOIL

	e_{min} (d_{max}) (g/cm^3)	e_{max} (d_{min}) (g/cm^3)	Compacted soil density (g/cm^3)
Material 2	0.34 (1,97)	0.6 (1,65)	1.93
Material 1	0.36 (1,94)	0.57 (1,68)	1.91

For the tests, the material were compacted to a relative density of 90%; this relative density corresponds for "material 1" to a density equal to 1.91 g/cm^3 and for "material 2" to a density equal to 1.93 g/cm^3.

The materials were introduced in the columns by layers of 10 cm of thickness. The initial porosity of "material 1" is equal to 0.27, that corresponding to "material 2" is equal to 0.26.

A drain was introduced at the bottom of the cell to ensure a good water and nutrition injection. The drain is made using the

Terzaghi rule filter with grains between 10 and 12.5mm for "material 1" and between 16 and 20mm for "material 2". The tests were performed at 12°C.

Before use, the nutrition solutions were preserved at a temperature lower than 10°C. Then they were diluted to a 1:40 ratio for the tests. The time between the storage and the injection was carefully optimized to avoid the deterioration of the solution.

The Clogging Tests: The clogging tests were conducted in two phases. In the first phase, the water is injected in the material under a constant hydraulic head until the stabilization of the outflow. The second phase corresponds to the injection of nutrition, under the same hydraulic head, until the outflow becomes nearly equal to 0. These two phases correspond to the "standard phase". It is important to mention that the tests are performed without the injection of bacteria and only the bacteria present in the soil participate in the clogging. The permeability is calculated using the Darcy law.

The Durability Tests: To determine the critical gradient (i_{cri}), the test consists in gradually increasing the entrance hydraulic head until the destruction of the clogging. The state of the clogging is evaluated by the measurement of the outlet flow.

The hydraulic head tests are conducted in two steps. The first one is the "standard phase". When clogging is reached, the cycles of hydraulic head are applied. The cycles consist in increasing the hydraulic head up to half the critical gradient ($i_{cri}/2$) during one day, then in decreasing it to its initial value during one day. This operation is repeated 10 times. During the application of the cycles, the flow is not measured; it is measured only at the end of the cycles.

The experimental protocol used for the desaturation-resaturation cycles consists of the "standard phase" followed by (i) the desaturation of the column during one day by opening the valves at the bottom of the column and (ii) its resaturation by filling the column with water. Each step takes one day. These two steps are repeated 10 times. The flow is measured at the end of the cycles.

III. RESULTS

The clogging test: The evolution of the flow as a function of time is presented in Fig. 3 (a) for "material 1" and in Fig. 3 (b) for "material 2".

Both curves show a first phase corresponding to the injection of water. The stabilization of the water flow occurs at day 12 for "material 1" and after 20 days for "material 2". The figures show that the stabilization of the outlet flow is not immediately obtained and that an increase of the flow can be noted before its stabilization and the establishment of the steady state flow.

The Material 1: Concerning this material, after the nutrition solution injection, the flow decreases quickly and reaches a value close to zero. The quick decrease of the flow is observed in other works ([13], [14]). Between day 42 and day 55 the nutrition injection was stopped and increase of the flow was observed. The increase of the flow suggests that the clogging is not stable after the injection at day 42; the nutrition reserve is not enough to ensure the bacteria growth. The injection of nutrition solution since day 55 reduces the flow which reaches a very low value at day 75. Between days 75 and 87, the flow remains constant, without an additional injection of nutrition. At this time, the clogging is considered stable and the hydraulic head increase begins for the durability test. At the end of water injection, the permeability of the soil is 4 10^{-5} m/s, at the end of the clogging test; the permeability is equal to 2 10^{-6} m/s.

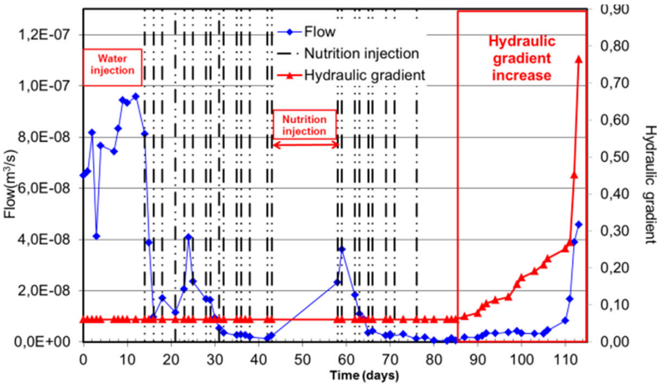

Fig. 3 (a) Evolution of the flow versus time during clogging for the "material 1"

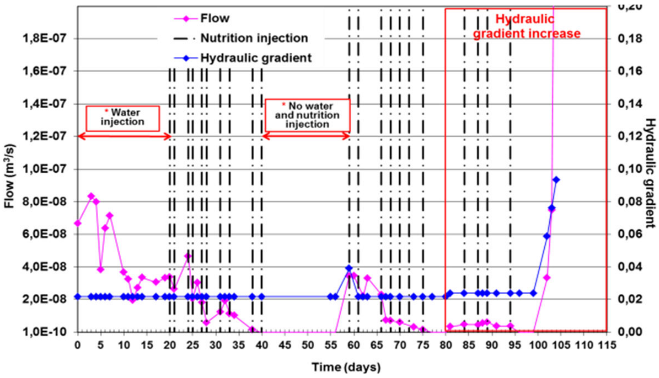

Fig. 3 (b) Evolution of the flow versus time during clogging for the "material 2"

The evolution of the hydraulic head is presented as a function of the elevation of the measurement point is presented in Fig. 4 (a). The curves show a decrease of the hydraulic head at the upper part of the column, suggesting a progressive clogging of the sample in the upper part. At day 83, the clogging occurs in the whole sample. This result is in agreement with the results derived from the curves of the evolution of flow versus time. The permeability of the sample at day 83 is equal to 10^{-6} m/s and is homogeneous in the cell. There is a significant decrease of the permeability after the injection of nutrition.

"Material 2" shows a gradual decrease of the outlet flow after the injection of nutrition. The flow reaches a value equal to 0 at day 40. Between days 40 and 55, an arrest of the nutrition and water injection was imposed which causes the increase of the flow. In addition, an accidental increase of the hydraulic gradient caused the increase of the flow at day 56, due to the difficulty to maintain the hydraulic head constant in reason of its low value. After decreasing the hydraulic head to the initial value, the nutrition was re-injected between days 60 to 75. The flow decreases and remains constant between days 75 and 80. At day 80, the hydraulic head increase begins, as will be detailed later.

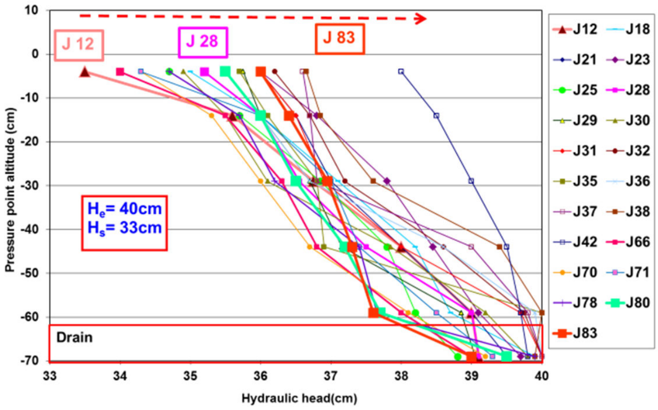

Fig. 4 (a) Evolution of the hydraulic head during the test on "material 1"

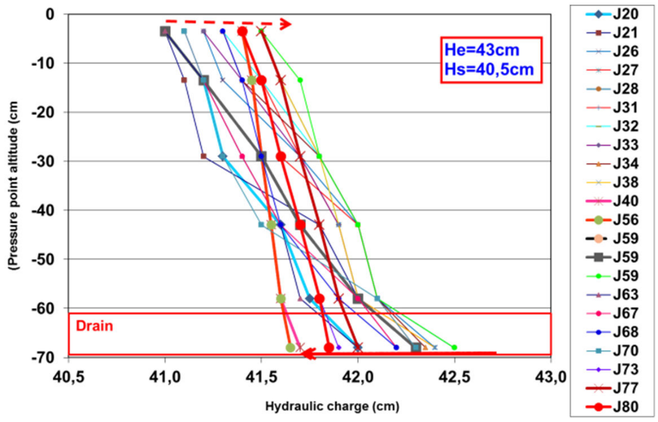

Fig. 4 (b) Evolution of the hydraulic head during the test on "material 2"

Fig. 4 (b) shows the evolution of the hydraulic head after the injection of nutrition. As mentioned before, the hydraulic head difference is very low, it is not easy to obtain a clear tendency concerning the place in which clogging occurs. It seems that, on day 95, the column is totally clogged. The permeability of the soil after injection decreases to 10^{-7} m/s

The durability tests results: In order to evaluate the stability and the resistance of the clogged material, the hydraulic head was increased in order to determine the critical gradient corresponding to the destruction of the clogging.

a/ The Determination of the Critical Gradient: Fig. 3 (a) shows that for "material 1" the flow remains constant for hydraulic gradients varying from 0.06 to 0.44. When the applied hydraulic gradient reaches a value equal to 0.44 the flow increases. For a hydraulic gradient equal to 1, the flow is equal to 4.58 10^{-8}m^3/s. However, this value is lower than the value of the flow just before the injection of nutrition, which was around 10^{-7} m^3/s. This result means that part of the clogging remains in the material even if the hydraulic gradient is increased to a value equal to 1. Therefore, it can be concluded that the sample treatment presents a good resistance to the increase of the hydraulic gradient.

In Fig. 6 (a), the evolution of the flow as a function of the hydraulic gradient is presented. The critical gradient is defined as the change in the slope of the curve. In this case, the critical gradient is equal to 0.765.

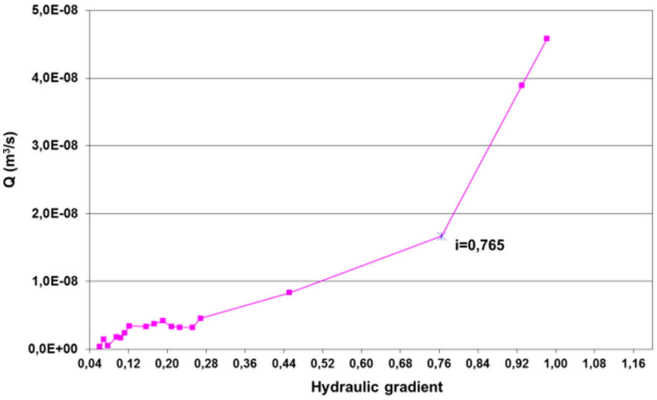

Fig. 6 (a) Determination of the critical hydraulic gradient for the "material 1"

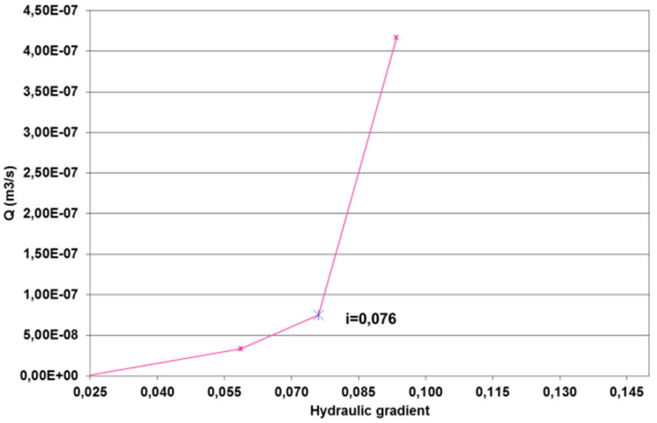

Fig. 6 (b) Determination of the critical hydraulic gradient for the "material 2"

For "material 2", the results corresponding to the increase of the hydraulic gradient are presented in Fig. 3 (b). The results show that a fast increase of the flow is observed when the hydraulic gradient is increased. A hydraulic gradient equal to 0.06 leads to a flow value higher than the flow before the injection of nutrition. Indeed, when the nutrition is injected, the flow is equal to 3.3$10^{-8}$ m^3/s, for a hydraulic gradient equal to 0.06, the flow reaches 8 10^{-8} m^3/s. Owing to the curve presented in Fig. 6 (b), the slope of the curve changes for a hydraulic gradient equal to 0.076.

b/ The Cycles of Hydraulic Head: The aim of this test is to evaluate the durability of the clogged material under repetitive cycles of hydraulic head. The results of this test are presented in Figs. 7 (a) and (b) for "material 1" and "material 2", respectively.

For "material 1", the results show that, after the cycles, the flow reaches a value of 0.8 10^{-8} m^3/s. Compared to the value of the flow before the injection of nutrition this value is very low. The result suggests that the clogged material presents a good durability to hydraulic gradient cycles.

In contrast, "material 2" shows a drastic increase after the hydraulic head cycles. As shown in Fig. 7 (b), the flow measured after the application of the cycles increases to 1.6 10^{-6} m^3/s.

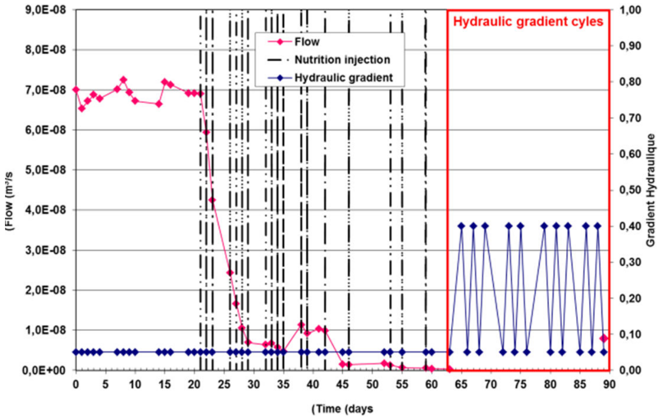

Fig. 7 (a) Evolution of the "material 1" flow during the hydraulic gradient cycles

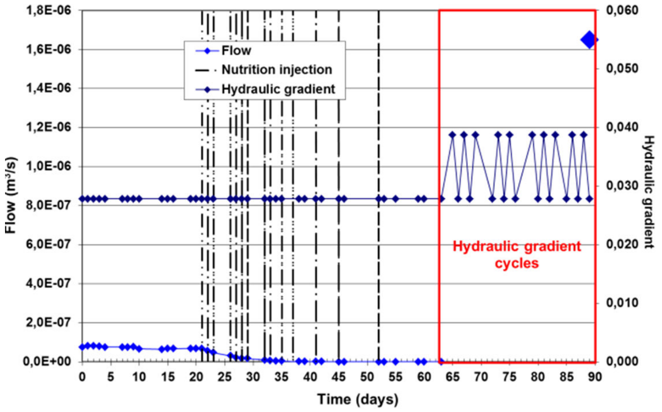

Fig. 7 (b) Evolution of the " material 2" flow during the hydraulic gradient cycles

c/ The Cycles of Desaturation-Resaturation: Figs. 8 (a) and 8 (b) present the evolution of the flow after the desaturation phase of the cycles. The aim of these tests is to study the durability of the studied clogged materials when a variation of the level of water happens.

As concerns "material 1", a very slight increase of the flow is observed after the application of the cycles. Indeed, the flow reaches a value equal to 2 10^{-9} m^3/s (the flow at the beginning of the injection of nutrition was equal to 6.7 10^{-8} m^3/s, and at the end of the clogging test it is near to 0). The result is not very good for "material 2" because the flow increases after the cycles to 4.23 10^{-8} m^3/s, which corresponds to half the flow value at the beginning of the nutrition injection (which was equal to 7 10^{-8} m^3/s).

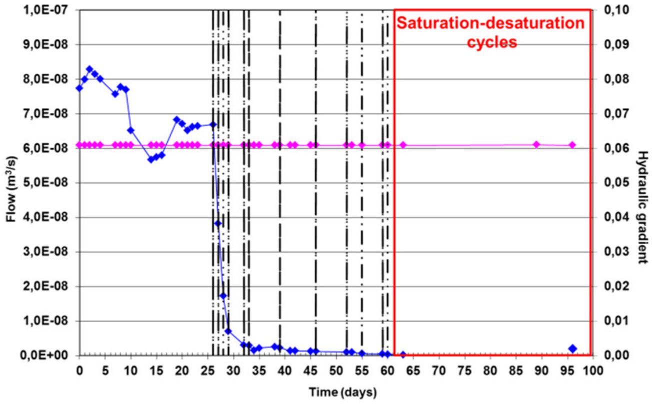

Fig. 8 (a) Evolution of the "material 1" flow during the desaturation–resaturation test

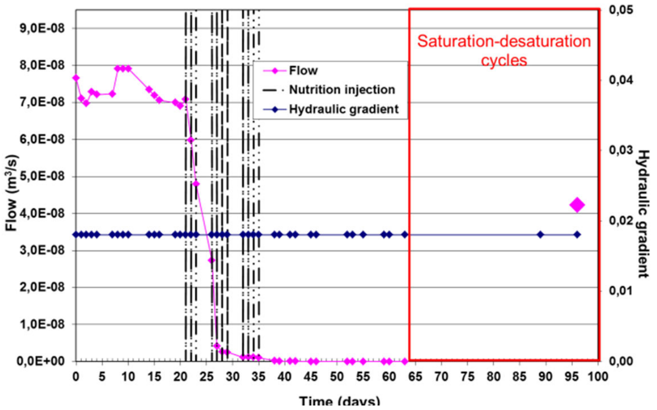

Fig. 8 (b) Evolution of the " material 2" flow during the desaturation–resaturation test

IV. DISCUSSION

The results show that for "material 1" and "material 2", the clogging occurs quickly after the injection of the nutrition.

A duration of 40 days is not sufficient to obtain a resistant clogging in the two soils. Indeed, stopping nutrition leads to an increase of the flow. The reserve of nutrition is not enough to ensure the biological process to continue.

The critical hydraulic gradient is equal to 0,765 for "material 1" and to 0.076 for "material 2". The critical hydraulic value corresponding to "material 1" causes the increase of the flow but the flow remains lower than the flow at the beginning of the nutrition injection. It seems that clogging is not totally destroyed after the increase of the hydraulic gradient. In opposition, the increase of the hydraulic gradient in the case of "material 2" induces a drastic increase of the outlet flow, which becomes higher than that at the beginning of the nutrition injection. This result suggests that the totality of the clogging is destroyed and that leaching of the material also happens.

The durability tests suggest that "material 1" presents a better resistance to the cycles of hydraulic head than "material 2". Indeed, for "material 2", a very slight increase of the outlet

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flow is observed after the hydraulic head increase. Concerning "material 2" the outlet flow is multiplied by 25.

The resistance to the desaturation-saturation cycles results show an increase of outlet flow, as observed below. "Material 1" shows a better resistance than "material 2". Nevertheless, the flow in this case does not exceed the flow before the nutrition injection.

In this study the injection of the nutrition is performed under constant conditions and it was chosen to apply for each soil the same contact time between the grains and the nutrition. This condition was satisfied by imposing an injection velocity corresponding to a travel time equal to 24 hours. The initial porosity of the two soils is nearly the same. So, the difference of the results is due the difference between the maximum grain sizes of the materials. The finer "material 1" is formed by grains with diameters varying between 0.3 and 3 mm whereas the "material 2" is formed by grains with diameters varying between 1 and 10 mm. So, "material 2" is poor in fine grains. Clogging is better in the case of material 1. The results can be compared to the results presented by [9], [10], [24]. Indeed, the results presented in this work show that clogging is better in the case of the finer materials. In the same sense, [25] and [26] suggested that, to avoid bioclogging, the presence of coarser grains is necessary.

V. CONCLUSION

The durability of the bioclogging in "material 1" is better than that of "material 2". Indded, "material 1" is formed by grain sizes between 0.4 and 4mm."Material 2" is composed of grains with size varying between 1 and 10mm. The presence fine ameliorates the resistance of clogging and its durability.

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