Experimental and parametric study of clayey sludge filtration by various geotextiles

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ABSTRACT: The geotextile filtration of fine particles in suspension in water, or of clayey sludge, is more complex than the filtration of granular soils in suspension; in practice in such application, flocculants are generally used to postpone the apparition of the filter cake. The present study, realized without flocculent, has been established to determine the influence of the geotextile characteristics on the formation of the filter cake. The role of key parameters, like the type of soil, the concentration of fines, the type of water flow and the type of geotextile is analysed and discussed in detail. The performance of the different systems is compared based on the analysis of the retained and passing soils, the time for clogging and the global characteristic of the filter cake. The settling of the fines in the testing device and its influence on the results is also analysed. The different cake's formation processes, the different particle sizes distributions and the different specific cake resistances are evaluated, analysed and discussed. As the permeability of the system changes with the creation of the filter cake, the initial permeability of the geotextile is less important than the influence of the geotextile on the creation process of the filter cake and its characteristics. The obtained results and comparisons are reasonably good. This study allows showing for the soils tested, that geotextiles with specific properties allow reaching a best compromise between the opening size and the support of a filter cake suitable for the long-term permeability.

Keywords: geosynthetics, geotextiles, filtration, clayey sludge, fine, suspension

1 INTRODUCTION

In some filtration applications, the geotextiles may be placed unconfined with the upstream soil or in contact with soft, saturated fine soils. In such cases, as far as the soil is not consolidated, the water flow may easily erode the soil and get charged with fines. In case of large characteristic opening size, the geotextile will let pass a large amount of fine particles into the drainage system which will cause in most cases it's clogging. But more generally, the fine particles will progressively accumulate at the surface and inside the geotextile; this will lead to an increase of the water head loss at the level of the geotextile reducing the water flow passing through the geotextile. This process leads to the reduction of the water velocity, then of the corresponding erosion and consequently of the amount of fine particles in suspension reaching the geotextile. Understanding the process of retention of the fine particles by the geotextile and predicting the critical value of the water head loss in the geotextile is of a great interest. This phenomenon has been studied by some authors like (Le Coq, 1996) who proposed a model describing the increase of head loss through a filter due to clogging and (Faure, et al., 2006) for the prediction of geotextile clogging during filtration of suspended solids.

The filtration of fine particles in suspension by geotextiles is also used in environmental application for the dewatering of sludge. In this case the sludge is generally introduced inside a geotextile tube, or a container, which retains the solid fraction of the sludge and let pass most of the liquid effluent. Flocculants are generally necessary to postpone, or to avoid, the apparition of a low-permeable filter cake at the surface of the geotextile and to allow a correct filling of the container by the solid particles (Lawson, 2006), (Satyamurthy & Bhatia, 2009).

More rarely the filtration of fine particles in suspension by geotextiles without flocculants has also been studied in the case of drainage of mining sludge. Recently, studies of filtration of fine-grained mineral sludge confirm the feasibility of geotextile filtration for dewatering of high clay content materials with low hydraulic conductivity (Bourgès-Gastaud, et al., 2014).

2 DESCRIPTION OF THE EXPERIMENTAL STUDY

Considering the present knowledge on the filtration of fines in suspension by geotextile without using additives, it seemed important to launch a study, with the goal to precise the influence of most important geotextile's characteristics on the formation of the filter cake from various clayey sludges and on the evolution of the filtration system "cake-geotextile" over time. The choice of a systematic parametric approach has been made: the influence of several key parameters on the filtration system behavior has been evaluated, including: (a) the type of soil (e.g. well graded or uniform), (b) several concentration of fines, (c) the type of water flow (e.g. constant flow or constant head) and (d) several types of geotextile. The study shows the compared performance of the tested geotextile filters, based on the analysis of the retained and passing soils, before and after the formation of the filter cake.

2.1 *Assumptions, test parameters and test conditions*

2.1.1 *Type of soils used for the filtration tests*

It is reasonable to think that the filtration behavior is largely influenced by the type of the soil in suspension, defined by several parameters like distribution of particle size, the type of particles, the shape of the particles and/or the clay content and plasticity index. To reduce the number of tests, it has been decided in a first stage to check only the influence of the granularity curve shape. The choice has been made to use and combine well known soils (kaolinite and silt) to create the two soils used for these tests.

The particle size distributions of the two soils tested are presented in Figure 1. The soil, named (A), is a kaolinite with a uniform granularity (CU = 4.5) and the soil, named (B), is formed by the combination of kaolinite and silt (CU = 13) is a well graded fine soil.

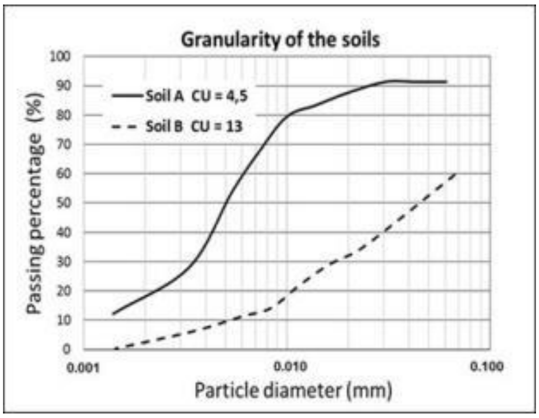


Figure 1. Particle size distribution of the different soils used in the filtration tests.

2.1.2 *Sludge properties, concentration of particles and flow conditions*

The two soils have been tested at different concentrations of particles for different flow conditions. For the lowest concentrations, a constant flow of the sludge has been used. A flow value of 0.5 L/min is maintained until a pressure of 40 kPa is reached upstream the geotextile filter; after the test is continued with a constant head. For the highest concentrations, a constant head condition (with a maximum of 10 kPa) has been used. Table 1 presents the different conditions of the tests performed.

Table 1. Assumptions of flow and solid fine concentrations tested.

Sludge flow condition	Concentration of solid particles (g/L)			
Constant head (10 kPa)	400 g/L	500 g/L	700 g/L	
Constant flow (0.5 L / min.)	70 g/L	100 g/L	200 g/L	300 g/L

2.1.3 *Testing device and setup of the apparatus*

Figure 2 presents the test cell used for the filtration of the sludge. Upstream a tank with a stirring tool allows maintaining a constant and uniform predefined concentration of fines in the incoming sludge. The monitored pumping system fixes and controls the flow conditions at the entrance of the filtration cell. A pressure sensor is placed at the top of the cell (Figure 3, left). The 15 cm diameter filtration geotextile is held by a metallic grid which avoids most of the deformation of the geotextile during the test. The passing sludge is regularly weighted during the filtration test and collected for further analysis.

It can be noted that the cell (volume $8.8*10^{-3}$ m^3) has been placed horizontally and the filtration geotextile vertically. This vertical position of the geotextile corresponds in fact to a relatively frequent situation in situ, like upstream vertical drainage-trench or on the side of dewatering tubes; it allows also a separation of the settling and sedimentation behavior from the filtration behavior.

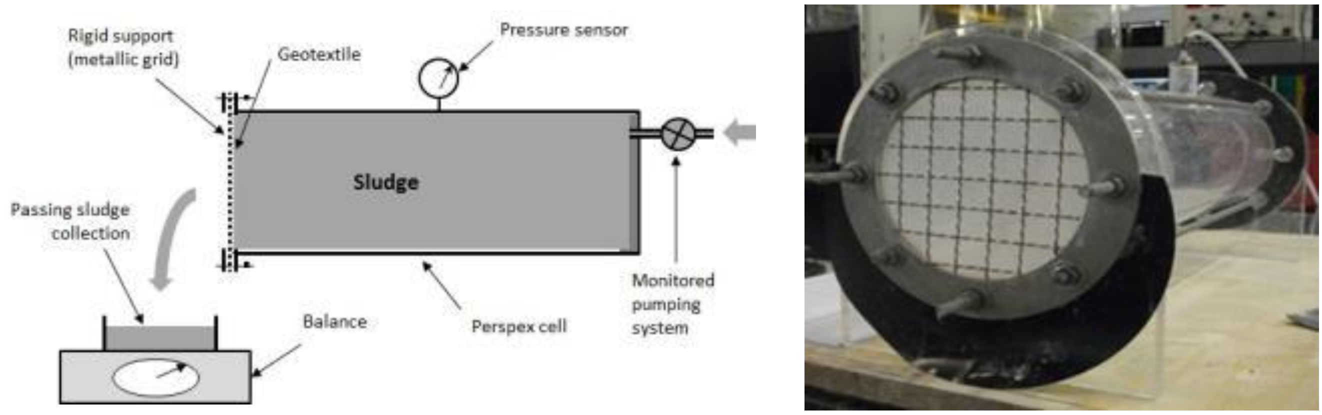


Figure 2. Principle of the test cell used for the filtration of the sludge (no scale) and view of the cell empty.

2.2 *Geotextiles tested and corresponding test conditions*

Table 2 presents the characteristics of the different geotextiles tested. To evaluate the influence of the different structures of the geotextiles with similar characteristic opening size, it has been decided to test a metallic sieve (W-2) (O_{90} = 63 µm) to simulate a woven with a characteristic opening size close to 50 – 60 µm; this is due to the difficulty to find woven geotextile with such a small opening size.

Table 2. Measured identification and hydraulic characteristics of the different geotextiles tested.

Geotextile	Structure	O_{90} (µm) (EN ISO 12956)	Water capacity normal to plane (EN ISO 11058)	Mass per unit area (EN ISO 9864)
(NWTB-1)	Thermally bonded Nonwoven	< 50 µm	8 mm/s	160 g/m²
(NWTB-2)		< 50 µm	1 mm/s	220 g/m²
(NWTB-3)		61 µm	20 mm/s	125 g/m²
(NWTB-4)		140 µm	50 mm/s	125 g/m²
(NWMB-1)	Needle punched Nonwoven	91 µm	105 mm/s	190 g/m²
(NWMB-2)		54 µm	14 mm/s	800 g/m²
(W-1)	Woven	109 µm	13 mm/s	327 g/m²
(W-2)		63 µm	(127 mm/s)	(-)

3 EXPERIMENTAL FILTRATION STUDY RESULTS

A first set of tests have been realized both for the constant flow and constant head conditions with the different geotextiles and different soils and fines concentrations. These tests have been stopped based on visual observation when no more passing fines were observed. This allows studying the filtration controlled by the geotextile. To precise the filtration behavior controlled by the formation of the filter cake, in the case of the constant head conditions, some of the tests have been repeated with a longer duration up to 90 minutes. Figure 3 shows the regular measurement of passing sludge to evaluate the fines passing through the geotextile during the process of the test.

Figure 3. During the process of the test, passing sludge is regularly measured to evaluate the fines passing through the geotextile;

3.1 *Observations of the different behaviors*

Depending on the type of geotextiles, the concentration and the hydraulic conditions, different behaviors have been observed:

- in a first case, a large quantity of sludge is passing through the geotextile, the cell cannot be filled, no stable filtration system is established; this is for instance the case for the NWMB-2 when tested under constant flow conditions with the soil B and a concentration of C_s = 200 g/L (Figure 4);
- in a second case, a limited quantity of sludge is passing through the geotextile, the cell is filled and a stabilized system is observed, either;
  a) with practically complete clogging of the geotextile after a certain period of time; no fines but also nearly no water is passing at the end of the test;
  b) or with a stabilized filtration system; after a certain period of time, water is still passing through the system and, either no fines are passing, or some fines still continue to pass; this last situation has been observed with NWMB-2 when tested under constant head with the soil B and a concentration of Cs = 500 g/L (Figure 8).

Figure 4. Example of test where the cell could not be filled (e.g. constant flow NWMB-2 / C_s = 200 g/L ; soil B)

3.2 *Filtration controlled by the geotextile*

3.2.1 *Constant flow conditions*

For the well graded soil (B), it could be observed that, due to the low concentrations in most of the tests, the cell could not be filled. It has been observed that the coarser particles are settling in the cell before reaching the geotextile filter and then the finest particles in suspension reaching the filter are too small to be filtered, and/or to create a cake.

Figure 4 shows a view of the cell after the test in constant flow conditions with the effect of the sedimentation and the settling inside the cell. It can be seen that a large amount of fines have filled the bottom half of the cell.

Nevertheless it could be observed that only the product (NWTB-1) allows a retention of the fines in suspension and the creation of a filtration system for the two highest nominal concentrations (200 g/L and 300 g/L). This probably linked to both the small opening size and the specific structure of this product.

On the contrary for the uniform soil (A), a better filtering behavior is observed with the creation of the filtration system in most of the geotextiles tested.

3.2.2 *Settling of particles inside the sludge*

The settling observed inside the cell at the end of most of the tests is probably linked to the type and the size of the particles. It is interesting to try to evaluate the theoretical settling of the particles during the test. The constant flow (Fw) is equal to 0,5 L/min, this means that, considering that the diameter of the cell is 15 cm and its length 50 cm, the "transit time" (tt) necessary for a fine particle to transit between the entrance in the cell and the surface of the filter geotextile can be evaluated to 17 minutes 40 seconds. Considering that (i) the entrance of the cell is placed opposite to the filter at the top of the cell (Figure 2) and (ii) the speed of settling of the particles can be calculated, assuming that the shape of the particles is spherical, it is possible to evaluate the size of the particles which are capable to reach the filter. It is clear that, during the duration of the test, the cell is progressively filled from the bottom by the coarser particles; this reduces the effective volume of the cell and then reduces the "transit time" of the fines (tt), if the flow (Fw) remains constant to 0.5 L/m.

Nevertheless, in a first approach, the following evaluation has been made for the very beginning of the test, when the coarser particles haven't started to fill the bottom of the cell. The calculation is realized with the assumption that the particles are spherical shape and that the terminal settling velocity of a fine particle in water can be estimated by Stokes law (1) valid for Reynolds number between (10^{-5} and 2):

$$\mathbf{V_t = D_h{}^2 g(\rho_p - \rho_w)/18\mu} \tag{1}$$

where V_t is the terminal settling velocity of the particle (m/s), D_h, the hydraulic diameter of particle (m), g, acceleration of gravity (m/s²), ρ_p, density of the particle (kg/m^3), ρ_w, density of water (kg/m^3) and μ, viscosity of the liquid (Ns/m^2).

The effect of high particle concentrations on the settling velocity is taken into account according equation (2) and allows evaluating the theoretical settling ($S_{theo\,h}$ (tt)) during the "transit time" depending on the diameter of the particles.

$$\mathbf{V_h = \varepsilon^n V_t} \tag{2}$$

where V_h is the hindered settling velocity of the particle (m/s), V_t the terminal settling velocity of the particle (m/s), ε, the ratio of the volume of liquid over the volume of sludge and n, the exponent (n = 3.65 for $\varepsilon > 0.6$) (Lydersen, 1981).

If this theoretical hindered settling (S_{theo} h (tt)) is higher than the diameter of the cell, the corresponding particle will not reach the filter. If the particles can be considered spherical, the smallest particles (e.g. with a diameter Dh of 10 μm or smaller) will reach the filter, but the largest particles (e.g. with a diameter Dh of 20 μm, or larger) will not reach the filter and will accumulate at the bottom of the cell (Figure 5).

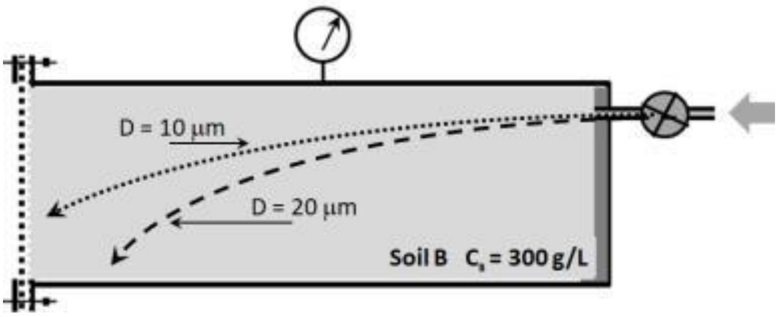


Figure 5. Principle of the influence of the particles settling during the test of the soil B (C_s = 300 g/L). .

Finally it has been observed that the geotextiles of larger opening size (NWMB-1; O_{90} = 91 μm) and (W-1; O_{90} = 109 μm) cannot block the fines and the cell cannot be filled. For the other geotextiles, a filter behavior is observed with a reduction of the mass of passing sludge compared to the theoretical flow;

from the higher reduction to the lower, the geotextiles are classified as follows, for the same concentration (100 g/L): (NWTB-1), (NWMB-2), (W-2). Similarly for a same geotextile (NWTB-1) a higher reduction of the mass of passing sludge is observed when the concentration increases. These results can also be shown in Figure 6 by the use of the efficiency ratio: (solid mass retained in the filtration cell) divided by (sludge mass passing through the geotextile).

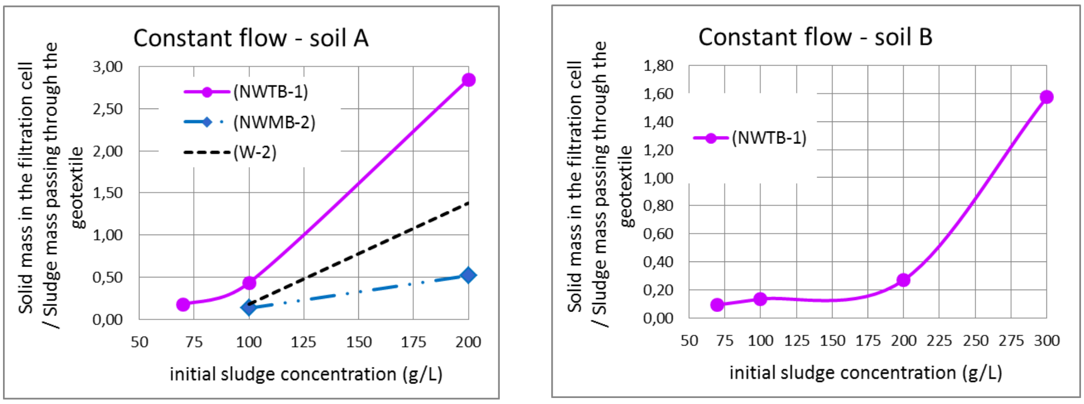
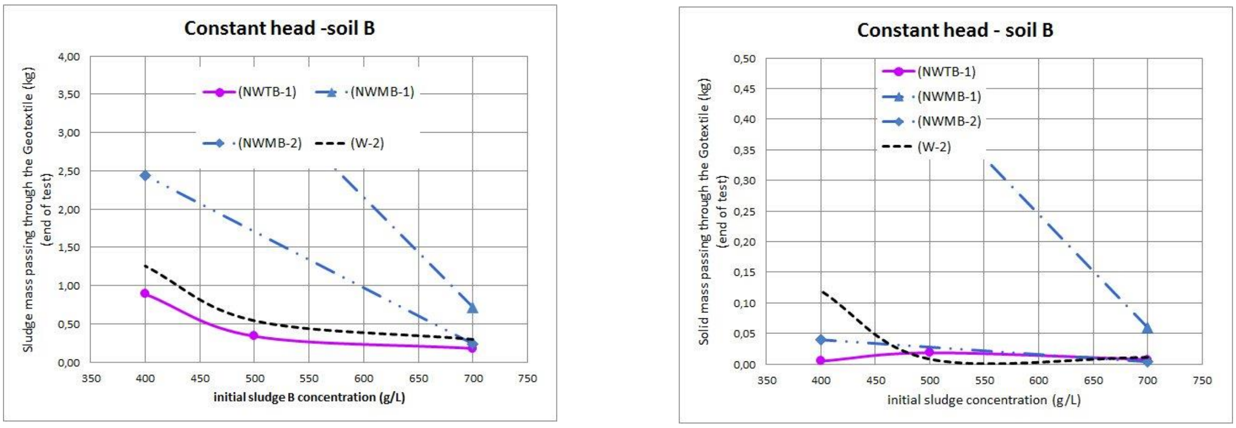


Figure 6. Compared ratio of the (solid mass retained in the filtration cell) divided by the (sludge mass passing through the geotextile) depending on the geotextile and the initial sludge concentration

In this case it can be observed from Figure 1 that 80% of the particles of the soil (A) have a diameter smaller than 10 µm. If, like for the soil (B), the assumption of spherical particles is considered as acceptable, the evaluation of the settling of the particles inside the cell during the tests is similar and 80% of the particles in suspension in the cell reach the geotextile filter. This can explain the creation of the filter cake in most of the tests.

3.2.3 *Constant head conditions*

For the well graded soil (B) is has been observed that a large amount of tests (11/20) the filtration could not be stabilized and that a large amount of fines continues to pass through the geotextile filter at the end of the test. Nevertheless for the other tests, Figure 7 presents the compared behaviors depending on the geotextile and the initial sludge concentration, at the end of the tests (stopped based on observation) and for constant head conditions.



Sludge mass passing through the geotextile measured at the end of the test — *Solid (fines) mass passing through the geotextile measured at the end of the test*

Figure 7. Soil (B) - Compared filtration behaviors based on the passing sludge (or solid fines) depending on the geotextile and the initial sludge concentration in constant head conditions.
(*Phase where the filtration is controlled by the geotextile*).

It allows comparing the different products:

- it can be observed that the mass of sludge, and similarly the mass of fines, passing through the geotextile decreases when the fines concentration in the sludge increases; this can be explained by a quicker creation of the cake in contact of the geotextile in case of an higher concentration of fine;
- the geotextiles of higher characteristic opening size (e.g. NWMB-1) let pass more sludge, and thus more fines, during the test;

- if the geotextiles with a thermobonded structure seem to allow a better stabilization than the mechanically bonded products, it appears that, for the same geotextile structure, a small opening size is a key parameter to allow the creation of a stable filtration system;
- based on the comparison of the results between the NWTB's and W's on one side and the NWMB's on the other side, considering that the number of constrictions is generally around 25 to 50 for mechanically bounded nonwovens and equal or closed to the unity for woven and thermally bonded nonwovens, it cannot be established that the number of constrictions is a relevant parameter for evaluating the filtration of fine in suspensions.

3.3 *Filtration controlled by formation of a filter cake*

As the time for creation of the filter cake varies depending on the type of geotextile, it is also interesting to evaluate the average passing quantities (flow of sludge, solid fines and water) and to observe the shapes of the curve of evolution of these parameters after the creation of the filter cake. This has been realized with a second series of tests with duration of 90 minutes. Figure 8 shows one example of a filter cake created during these tests. Figure 9 shows the evolution of the sludge mass passing through the geotextile and the solid mass passing during time. It can be seen that for the (NWMB-2) the fines continue to pass through the geotextile during all the duration of the test, where the (NWTB-1) and the (W-2) stop the passing of the fines after a certain time, but still allow the water to pass.

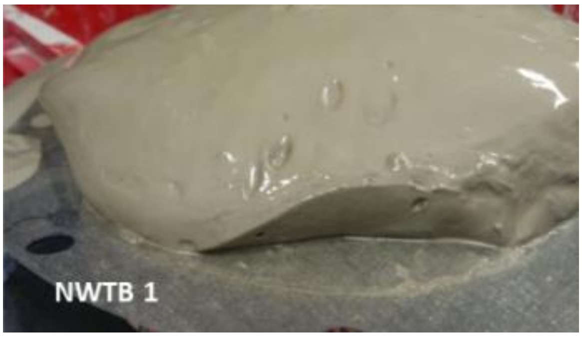


Figure 8. Cake formed with NWTB-1 in the constant head process, soil B C_s = 500 g/L.

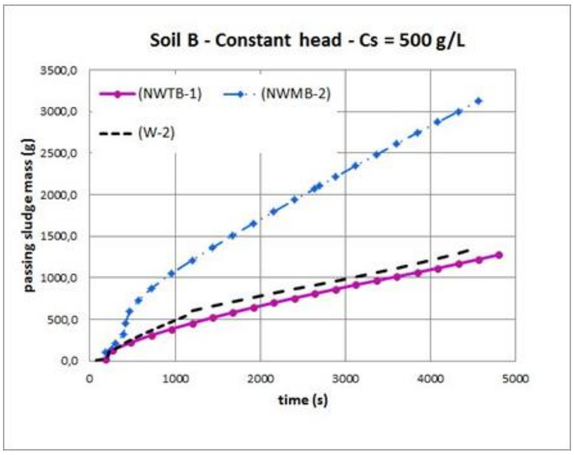
When a filter cake may deposes upstream on the geotextile, resulting in a filtration process that is controlled by the buildup of head loss across the filter cake which induces a pressure drop. To model this pressure drop during filtering, it can be proposed to use a theoretical equation developed to model solid/liquid separation process (Kozeny, 1927). In this way, the pressure drop may be estimated by the equation (3), assuming an incompressible filter cake:

$$\frac{dV}{dt} = \frac{\Delta p_f A}{\mu\left(\frac{\alpha C_S V}{A} + R_m\right)} \tag{1}$$

where A is the effective area of filtration (m²), V, the volume of filtrate (m^3), t, the filtration time (s), Δp_f, the pressure drop through the filter cake (Pa), α, the specific filter cake resistance (m/kg), R_m, the filter medium resistance (m^{-1}), C_s, the concentration of slurry (kg/m^3) and μ, the viscosity of the liquid phase of the suspension (Ns/m^2). The integration of the differential equation and its rearrangement leads to (4):

$$\frac{t}{V} = \alpha(\mu C_s/2A^2\Delta p_f)V + R_m(\mu/A\Delta p_f) \tag{2}$$

The interpretation of the experimental data by a graph of t/V versus V allows the evaluation of the specific filter cake resistance α, the filter medium resistance R_m, and a rough verification of the assumption that the filter cake is incompressible. According to (Leu, 1986) the specific cake resistance (α) is in the range from 1.10^9 m/kg (for an easy filtration) to 1.10^{13} m/kg (for a difficult filtration). Assuming a viscosity of 1.002 10^{-3} Ns/m^2, the first evaluation of the cake resistance on the 90 minutes tests, shows that the cake resistance of the stable filters is in the range of 1,5 10^9 to 1,2 10^{10} for the soil B. The measurement of the compressibility by tests at different pressures (not yet undertaken in this study), will help to confirm this first approach of the specific filter cake resistances and to evaluate the effect of the pressure increase on the filtration rates. Nevertheless this first evaluation seems encouraging and confirms the interest to continue the investigation on the geotextiles showing a good behavior during the long duration testing.



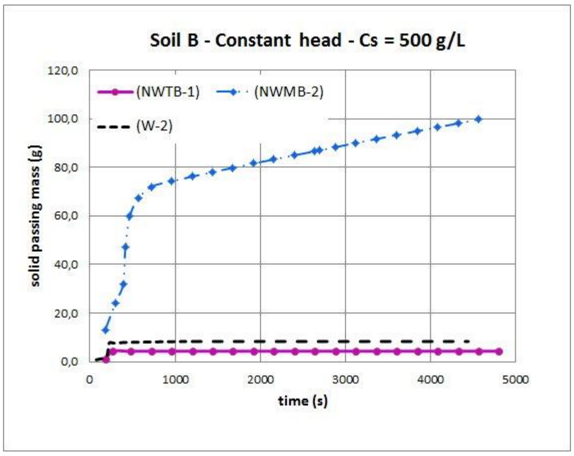


Figure 9. Sludge mass and solid mass passing through the geotextile during time for soil (B) in constant head conditions and for a fine concentration Cs = 500 g/L.
(*Phase where the filtration is controlled by formation of a filtration cake*).

4 CONCLUSION

The present study allowed to precise the influence of the geotextile characteristics on the filtration behavior when submitted to a flow of fines in suspension without flocculent. Different parameters have been analysed: type of soil (well graded or uniform), concentrations of fines (7, from 70 g/l to 700 g/l), type of water flow (constant flow or constant head) and types of geotextile (7). As a conclusion this study shows that the filtration of fines in suspension without flocculants by geotextiles remains a delicate topic. The results are largely influenced by the disposition of the filter (vertically or horizontally) due to the settling of the particles during the test. Finally, it appears that, for the soils tested, thin geotextiles with a lowest opening size ($O_{90} \leq 60$ µm) give the most promising results for filtration of fines without flocculants. Within these geotextiles, the thermally bonded nonwoven structure, best compromise between the opening size, the thickness and the support for a filter cake suitable for the long-term permeability, seems to offer the best behavior for most of the fine's concentrations with a well graded soil.

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