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Influence of the slurry initial conditions on the dewatering process evaluated by falling-head column test

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ABSTRACT
Geotextiles Closed Systems, GCS, has been used to dewatering a variety of high-water content sediments aiming to reduce the final volume of the residue at disposal. The geotextile retention capability to form a filter-cake that does not involve an excessive reduction of the hydraulic conductivity of the system is determinant to the success of the dewatering process. In addition, the grain size distribution of the solid phase, GSD, is tightly related to this success. There are two distinguishable phases in the process: the initial phase in which geotextile permeability controls the flow rate, and the post-filter-cake formation phase in which the retained sediments start to control the flow rate. The GSD play an important role in the retention of particles with a diameter smaller than the characteristic geotextile opening size by interlocking small particles between the bigger ones retained by the geotextile. However, it is difficult to determine how sensitive the dewatering process is to GSD variation. This work presented a discussion on how the increment in the coarse fraction of the GSD affects the filter-cake formation. The paper discusses the results of the falling-head column test performed to evaluate the behavior of a woven geotextile in the dewatering process of sediment with different GSD, in a turbulent flow condition at low initial solids content. The tests also evaluated the solids concentration in the effluent and water content in retained material. The obtained results indicate that a small amount of coarse material is sufficient to initiate the filter cake formation and has a greater impact on the effluent quality.

1. INTRODUCTION

The anthropic activity has a significant impact on the degradation process of water sources due to improper waste disposal. Waste with high water content, generated by various activities such as tailings, slurries, and sludge from mining activities, usually stored in dams; and heavy metal contaminated sediments stored in tailings ponds from industrial activity, are eventually discarded incorrectly in the environment (Lawson 2008).

An alternative to proper disposal of these wastes is the possibility of dewatering. Dewatering consists of removing excess free water contained in these wastes for the purpose of making them solid or semi-solid, facilitating their transport and disposal. One way to perform this dewatering is through Geosynthetic Closed or Confining Systems, GCS.

The use of GCS has gained space among the techniques employed in dewatering waste with high water content. Usually, the GCSs consist of geotextile pipes placed on a waterproof drainage bed. (Lawson 2016). The diameter of these pipes, length, and type of geotextile is a function of the type of waste to be drained. This configuration allows material encapsulation, isolation, dewatering and correct disposal of the waste, allowing control of the input and output variables of the system. (Guimarães et al. 2014).

The use of GCS in the treatment, containment, and disposal of high moisture residues, aims to achieve a considerable reduction in material volume through filtration mechanisms, allowing water to be drained from the material. The reduction in liquid content allows the physical state of the waste to be changed from liquid to semi-solid or solid, facilitating its proper handling, transportation, and disposal, as well as controlling the entire dewatering process (Bourgès-Gastaud et al. 2014; Lawson 2008).

A number of factors can influence sediment dewatering through geosynthetics. These factors are intrinsically linked with the nature of the material to be drained, with the ability of the geotextile to retain particles allowing fluid to pass and external factors such as the initial water content, the applied hydraulic gradient, and the containment boundary conditions (Segré 2013).

Giroud (2005) stresses that the retention of the particles does not occur trivial way, it depends on the particle size distribution of sediment particles and interlocking of the upstream geotextile's pore. The phenomenon of interlocking and particle accumulation on the geotextile constitutes the filter cake formation process. After the initial moments of dewatering, the filter cake dictates the GCS behavior regarding permeability and solids retention. The properties of the filter cake are critical to the success of the dewatering venture as it must be permeable enough to ensure water outflow.

The grain size distribution of the soil making up the sludge plays a key role in the success of the filter cake formation. However, there are cases where soil particle interlocking does not occur, i.e., in soils with wide grain size distribution. This can lead to the fine particles being carried between the coarse skeleton retained by the geotextile (Wei 2012).

In addition to the grain size distribution, factors such as grain shape, specific density, and cohesion, as well as external factors such as the confinement conditions of the system, the applied hydraulic gradient, the variation of water viscosity as a function of temperature and biological aspects as growth of microorganisms and leachate composition (Aydilek and Edil 2008).

Given that, the main challenge of using GCS is particle retention while maintaining the appropriate system permeability, it is necessary to understand the role of each of the variables involved in this process. This work aims to investigate the low solids sludge dewatering scenario under a turbulent flow regime using a woven geotextile. Four failing-head column tests under variable pressure were performed to evaluate the influence of small amounts of coarse material on the retention process of two other soils, as well as the influence of solids concentration and the relationship between the diameter of the particles that make up the sludge.

2. FALLING-HEAD DEWATERING TEST

The column test resembles the sedimentation column test, differing by the coupling of the geotextile at the end of the column, allowing the drainage and dewatering of the system. Following this principle, some column tests were designed, however, the test does not have standardization yet.

Moo-Young et al. (2002) used four woven geotextiles, two of polypropylene and two of polyester, to perform a pressure filtration test with five high water content materials. The high-water material was basically sludges of fines soil, d_{85} ranging from 0.021 to 0.19 mm and d_{50} from 0.005 to 0.04 mm, with an initial percent solid varying from 25.2 to 45.1%. They used a modified apparatus consisted of a chamber with an inner diameter of 128.45mm equipped with a system that applies the pressure by air. They observe that the permeability of the system drops considerably after the formation of the filter cake and that the final permeability has little relation with the geotextile property, indicating that the filter cake is the major agent controlling the permeability of the system. Also, they conclude that higher filtration pressure tends to increase the dewatering rate but does not help much to achieve a high final solid content of the sludge.

Kutay and Aydilek (2004), used a very similar apparatus to evaluate the dewaterability and the hydraulic compatibility of geotextile containers filled with fly ash and dredged sediments sludges. Four nonwoven and four woven geotextiles were used, as well as different combinations of nonwoven and woven geotextiles. The apparatus, a filter press, was made of a steel pipe with a diameter of 78mm and a height of 90mm with both ends sealed with caps with pressure and effluent collection holes. They, also, found that the most contribution in the dewatering process is related to the filter cake hydraulic properties. They pointed out that higher initial water contents usually resulted in greater piping, and the use of combined nonwoven/woven geotextile rather than a single woven geotextile greatly increase the retention performance of the system.

Alternatively to the pressurized test, Huang and Luo (2007) propose the utilization of a falling-head dewatering test apparatus (FHDT) to facilitates the evaluation of formation and the properties of filter cake, as it represents the gradual deposition of sediments upstream the geotextile. The apparatus was made of an acrylic cylinder with an inner diameter of 160mm and a total height of 540mm, supported by a square metal frame where the geotextile was attached. Four woven polypropylene geotextiles with different pore size aperture were used to evaluate the dewatering behavior. Their conclusions were in accordance with the above-mentioned author, despite the fact of a different application of pressure. In addition, they point out that a geotextile's opening size greater than a certain critical value shows unacceptably piping rates, however, after filter cake formation the piping rate drops to negligible values.

Weggel and Dortch (2012) used a very similar apparatus with simplifications. They executed thirty-four experiments of flow through a filter cake sediment accumulation on two woven polypropylene geotextiles aim to verify a theoretical model. They used three different types of sand: well-sorted Ottawa sand, fine sand, and well-graded sand. The slurries were suspended in a 1.37m-long Plexiglas tube with the geotextile attached to the bottom. They stress that for Ottawa sand the theoretical model doesn´t show a good agreement as shown to the other sediments. They attribute this behavior to the settling velocity of the sand and the rapid formation of the filter cake. In this case, the theoretical model indicated that the dewatering process was sensible to variations in the geotextile´s permeability.

3. MATERIALS

3.1 Granular Material

The granular material chosen was grounded quartz produced in the region of Guarulhos-SP, Brazil. Ground-quartz is a practically inert and homogeneous material when compared to natural soils or tailings, in order to facilitate the observation of the physical phenomenon of settling and filtration. In addition to being inert, the high hardness of quartz makes material wear difficult.

Three distinct Grain Size Distribution curves, GSD, were used: a raw material, named NG, with a considerable portion of grains smaller than 0.037mm; a material passing through the sieve # 80 (0.177 mm) and retained in the sieve # 100, named CG, and a material passing through the sieve # 100 and retained in the sieve # 400 (0.037 mm), named FG. The CG and FG materials were obtained by wet sieving.

The materials, both raw and sieved, were characterized as the specific density by the pycnometer method according to ABNT NBR NM 52 with a value of 2.67 g/cm³. The GSD was determined by the laser diffraction method via dry dispersion, according to ISO 13320. The GDS parameters are shown in Table 1 and the GSD curves are shown in Figure 1 Grain Size Distribution curves of the materials utilized 1. Table 1 shows also as the material CG meets Terzagui's filter requirements (Lambe and Whitmann 1969). The material CG meets the requirements for the material FG but fails to meet the second requirement for the material NG by a small margin. Noting that the Terzaghi's proposal was made to porous media filtration and no to particles in suspension.

Table 1 GSD analysis Summary

	CU[1]	CC[2]	d_{90}[3] (µm)	d_{50} (µm)	d_{10} (µm)	$(d_{15}f/d_{85}s)<5$	$4<(d_{15}f/d_{15}s)<20$	$(D_{50}f/d_{50}s<25$
CG	1.7	1.1	280	215	120			
FG	1.6	0.9	88.8	53.1	31.8	1.9	4.3	3.9
NG	9.3	1.1	87.8	31.7	4.0	2.2	**24.8**	6.9

[1]Coefficient of uniformity = $[d_{60}/d_{10}]$
[2]Coeficient of curvature = $[(d_{30})^2/(d_{60}d_{10})]$
[3]d_i = diameter such that i% of the particles is smaller

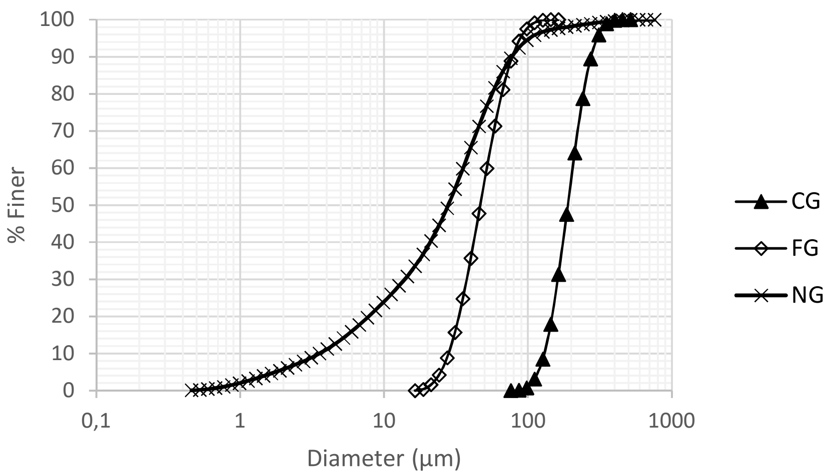


Figure 1 Grain Size Distribution curves of the materials utilized.

3.2 Geotextile Material

The geosynthetic material was a polypropylene woven geotextile, GTX-W, developed for dewatering applications. The physical characterization of the GTX-W was performed according to the respective standard: thickness, Tg, and mass per unit area, µ. Physical properties give an indication of the variability of the geotextile during its manufacturing process.

Also, the GTX-W was characterized by its hydraulic properties: characteristic opening size, O_{90}, according to ISO 12956, and Water Penetration, WPR, according to EN 13562. Figure 2 shows the visual aspect of the GTX-W and Table 2 presents the geotextile characteristics.

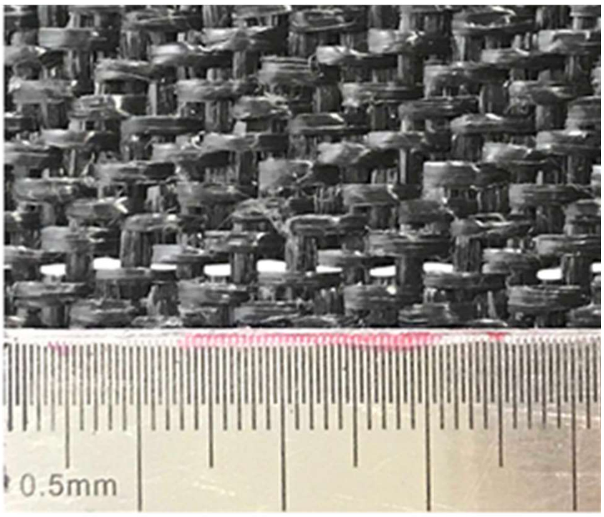


Figure 2 GTX-W Visual aspect

Table 2 GTX-W Properties

Property	Method	Value	CV¹ (%)
O_{90} (µm)	ISO 12956	240	-
µ (g/m²)	ISO 9864	454	2.0
T_g (mm)	ISO 9863-1	1.7	1.8
WPR	EN 13562:	3.6	3.6

¹CV = (Standard Deviation / Mean)*100

The flow velocity at a hydraulic load of 50mm through the geotextile in test conditions was unconventionally obtained using the same falling-head test apparatus used on the column tests. In this case, the V_{H50}, does not represent an index property, but the permeability of the geotextile under the column test conditions. The calculation methodology was analogous to the presented in ISO 11058. Table 3 shows the parameters of the best-fitted curve ($y= \alpha x^2 + \beta x$), the R^2 value indicates how good was the curve fit to the data point. As the geotextiles samples were unsaturated at the beginning of the test, the parameter t_w indicates how long the sample was in contact with water until started taking measurements. The curves and the data-points are shown in Figure 3.

Figure 4 shows the column during the test execution, the water was tinted with red liquid in a concentration of 4ml/L. It can be seen in Figure 4a how much air was incorporated by the turbulent flux inside the column. , the liquid is whitish when compared to instants shown in b), also in b) we can see the flotation of a layer of foam. This foam disperses very rapidly when the intake flux was ceased.

Table 3 Flow velocity test results

Samples	t_w(s)	α (s^{-2})	Β (s^{-1})	R^2	v_{H50} (mm/s)
1	18.8	0.0522	1.8589	0.904	17.9
2	18.4	0.0249	2.3925	0.831	17.7
3	18.5	0.0704	1.7264	0.891	17.1
4	18.4	0.0766	1.9964	0.907	15.7
5	18.1	0.0566	1.6591	0.982	18.5

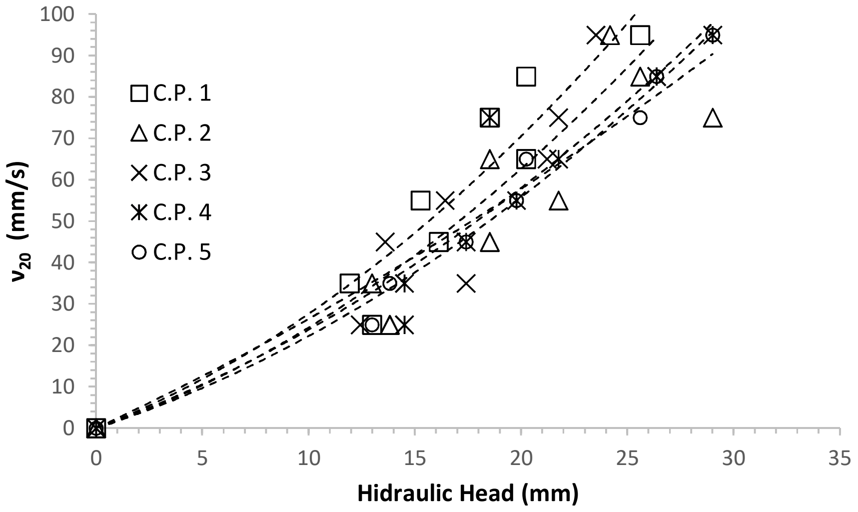
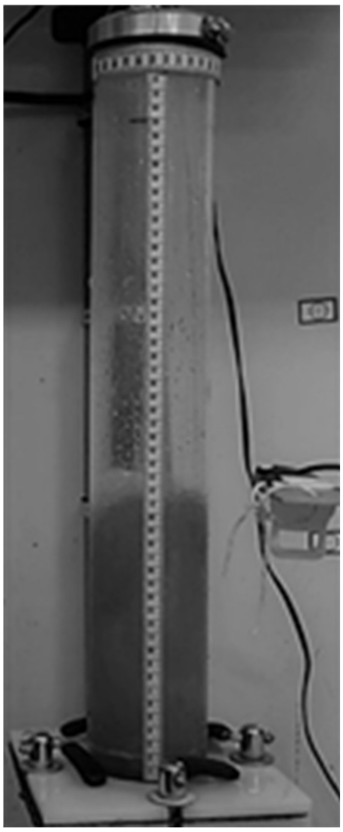
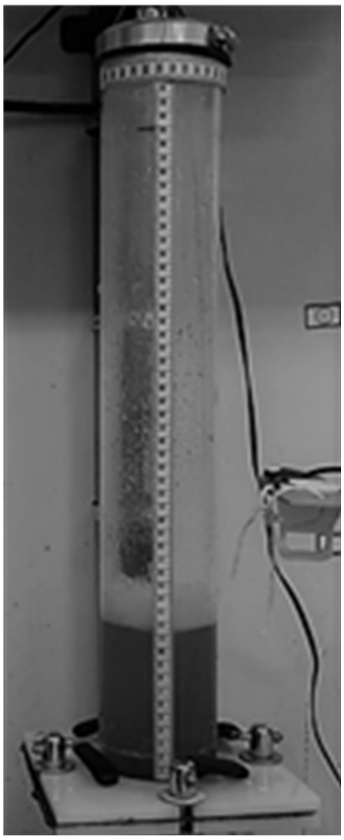


Figure 3 Flow velocity versus hydraulic head for GTX-W



(a) Filling of the column under turbulent flow

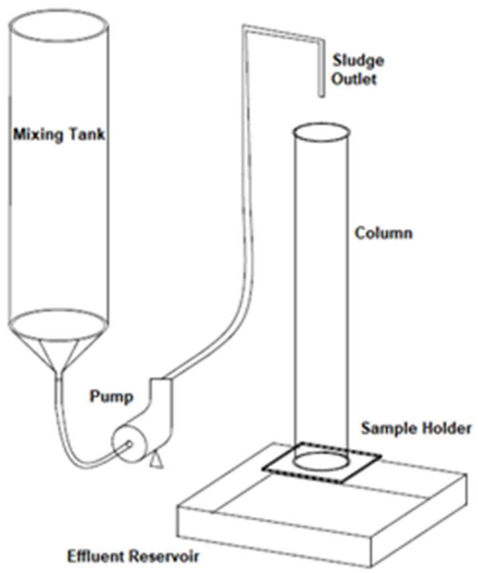


(b) Initial of measurement, no intake flow

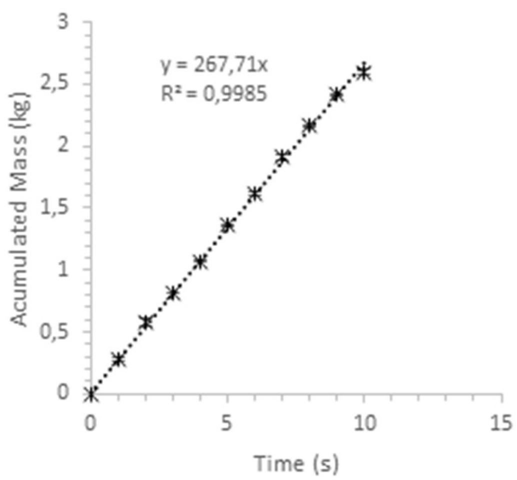
Figure 4 Determination of the flow velocity at 50mm of hydraulic load through the geotextile under test conditions

3.3 Falling-Head Column Test Apparatus

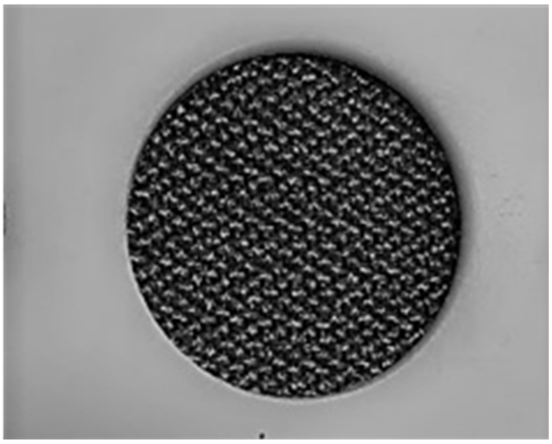
The test apparatus was similar to the by Weggel and Dortch (2012) with some modifications. It consists of an acrylic tube of 83mm inner diameter with a gripping system to attach the geotextile sample in the test position not allowing it to fold or deform. There was not used any wire mesh to support the geotextile sample, as it did not show any deformation caused by the slurry accumulation over it. The column was attached to a scale to measure the mass variation over time, and another scale was placed under the column to measure the outflow of the column, i.e., the dewatering flow rate. A hydraulic pump was used to inject the slurry in the column from a mixing tank. Figure 5a shows a diagram of the apparatus without the data acquisition, in Figure 5c can be seen the specimen in the test position, in Figure 5d, the same specimen can be seen during the test, notice that it does not show any deformation or sagging. The pump flow rate was determined by running three tests with an impermeable membrane. It was calculated by linear regression given a value of 267.7 g/s, a standard error of 1.7 g/s, and an R^2 of 0.999 as shown in Figure 5b.



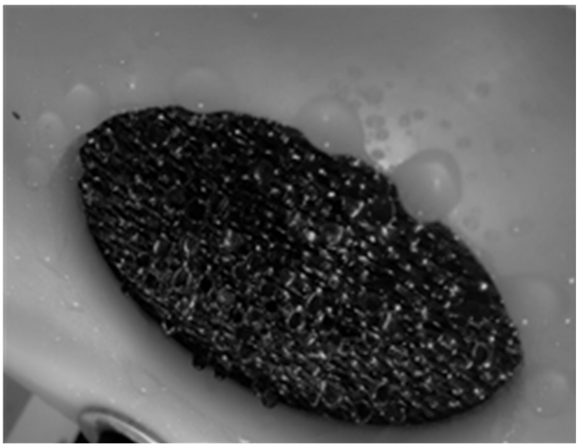
(a) Apparatus scheme



(b) Pump Flow rate determination



(c) The specimen before testing



(d) The specimen during testing

Figure 5 Apparatus and placed specimen

3.4 *Experiment Protocol*

The experiment was performed by mixing the corresponding fractions of each FG and CG with filtered water. The sludge was transferred to the mixing tank and pumped into the column. After the test, the effluent was collected and the solid fraction separated through sieve #400, the retained solid material was again separated by wet sieving on the sieves #100 and #400. The same was done with the retained material on the specimen.

4. RESULTS AND DISCUSSION

4.1 *Initial Conditions*

A set of four tests was carried out to investigate how sensible the filter cake formation phenomenon was at small changes in the grains size distribution curve of the sludge solid phase. The test N3C-S5 evaluated the addition of a small amount of coarse material to the material NG, while the test F3C-S5 evaluates the dewatering response of the same coarse material addition in the material FG. The tests F0C-S5 and F0C-S10 evaluated the influence of the initial solid concentration of the slugged, SC, in a critical dewatering condition. Table 4 shows a summary of the initial conditions of the tests. The SC of the solution changes slightly in the pumping process. The real solid condition, SC_{real}, was calculated by analyzing the effluent and the retained material. During the sieving process, some granular material was lost; it was fixed a 2% mass loss' threshold to discard a test.

Table 4 Falling-Head dewatering test initial conditions summary

Test	SC (%)[1]	SC_{real} (%)	Major GSD	$CG_{Nominal}$	CG_{Real} (%)	T_w (°C)	γ_S (g/cm³)	Mass Loss (%)
N3C-S5	5	5.1	NG	3	2.1	20.2	1.087	1.5
F3C-S5	5	5.2	FG	3	2.9	20.5	1.086	1.4
F0C-S5	5	9.9	FG	0	0.0	19.8	1.087	0.3
F0C-S10	10	4.7	FG	0	0.0	254	1.085	1.3

[1] SC – Solid content; T_w – water temperature; γ_S – Sludge density

4.2 *Filling and Dewatering Analysis*

During the test, the filling stop criterion was to achieve the sludge level, approximately at a height of 50cm, which corresponds to a mass of ~ 2700g. The pump was turned off when the sludge inside the tube gets to the target mark by a visual check.

Table 5 shows a summary of results for the filling and dewatering phases. The filling phase endpoint was characterized by the inflection in the filling curve, i.e., as the accumulated retained mass starts to decrease. The observed dewatering phase refers to the time interval where the water flows through the system under the hydraulic head, and the endpoint is characterized by the significant decrease in the slope of the dewatering curves. Table 5 shows a summary of the results for the filling and dewatering phase. The complete series of data is shown in Figure 6.

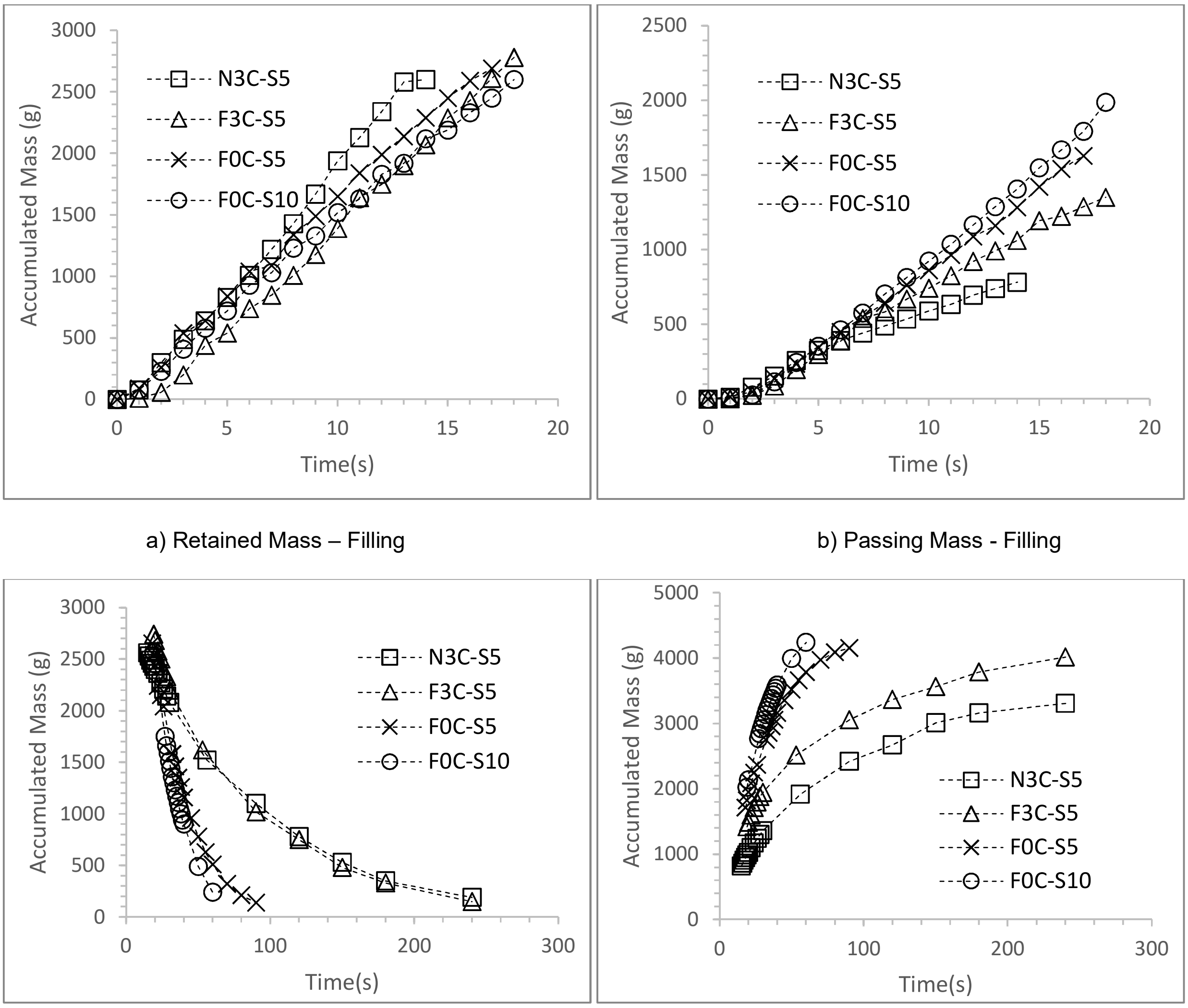
Table 5 Falling-Head dewatering test results summary

Test	Filling			Dewatering		
	Duration (s)	Passing (g)	Retained (g)	Duration (s)	Passing[1] (g)	Retained (g)
N3C-S5	14	782.6	2600	226	3309	150
F3C-S5	18	1351.3	2780	222	4017	190
F0C-S5	17	1629.7	2690	73	4156	140
F0C-S10	18	1987.6	2600	52	4360	110

[1] Total mass passing during the test, filling plus dewatering

The N3C-S5 shows the faster filling phase when compared with the other tests. As shown in Figure 6b, around t equal to 7s, passing mass curve starts to deviate from the other curves. It implies that the system permeability is sensible to the variations of the base soil GSD, as the N3C-S5 passing mass curve is bellow to all other tests. However, when analyzing the dewatering phase, the GSD variation of the base soil seems to have little influence in the system's permeability, this can be seen in Figure 6c and Figure 6d since de curves represented the same behavior.

The variation in the initial solid concentration seems to have little influence in the dewatering behavior, as a 100% increase in the initial solid concentration does not result in an expressive difference in the passing and retained mass curves from the tests F0C-S5 and F0C-S10, for both the filling and dewatering phase. The shift in the curves of passing mass, Figure 6d, is due to the difference of the pumped volume for each test to achieve the target filling hight, so, the curves started at different points.



a) Retained Mass – Filling

b) Passing Mass - Filling

c) Retained Mass – Dewatering

d) Passing Mass – Dewatering

Figure 6 Falling-Head dewatering test filling and dewatering curves

4.3 Retention Analyses

The retention of solid material was analyzed by the Filtration Efficiency, FE, that represents the variation of the initial Total Solids present in the sludge, TS_{ini}, and the total solid content in the effluent, TTS_{final} (Moo-Young et al. 2002):

$$FE\ (\%) = \frac{TS_{ini} - TTS_{final}}{TS_{ini}} x100 \qquad [1]$$

The Pipping Rate, that indicates how much solid mass pass-through the area unit of the geotextile, calculated by Equation 2, and the Solids Passing, SP, calculated by Equation 3, are also analyzed (Satyamurthy and Bhatia 2009):

$$\text{Pipping } (g/m^2) = \frac{TTS_{final}}{A}$$
[2]

$$\text{SP } (\%) = \frac{TTS_{final}}{TS_{ini}} x100$$ [3]

The results of the solids' retentions analyses are summarized in

Table 6. For the set of tests executed, the F3C-S5 shows the higher value of Filtration Efficiency. Despite having a lower permeability in the filling phase, N3C-S5 was not better in the solid retention capacity, presenting the lowest FE value and a Pipping 6.7% higher than that observed in the F3C-PS5 test. It indicated that the material CG was able to work as a filter to FC, but did not to NG. The Filtration Efficiency was calculated considering the total passing solids and the obtained value represents mean value.

The increase in initial solids concentration also does not appear to interfere with retention capacity, although, numerically, the mass of solids retained in F0C-PS10 is greater than that observed in the F0C-PS5. This does not translate into a significant difference in the observed values of FE and SP.

Table 6 Solids' retention results

	Solid retained (g)	Solid passing (g)	TS_{Ini} (%)	TTS_{Final} (%)	FE (%)	SP (%)	Pipping (g/m²)	Pipping/TS_{ini} (g/m²)
N3C-S5	14.53	157.39	5.13	4.70	8.5	91.6	29108	5670
F3C-S5	50.83	147.58	5.17	3.80	26.5	73.6	27276	5280
F0C-S5	19.52	195.25	4.65	4.23	9.1	90.9	36087	7758
F0C-S10	38.77	385.13	9.87	8;96	9.2	90.9	71181	7214

The Pipping values for the set F0C-PS5 / F0C-PS10 show a significant numerical difference, however, this cannot be interpreted as indicating that the system performs worse with increasing initial solids concentration. In order to analyze Pipping independently of the initial solid concentration, the values were normalized as a function of the initial solid concentration, Pipping / TS_{ini}, as shown in

Table 6. The normalized value of F0C-PS10 is 7.5% lower than the F0C-PS5 test, indicating little interference from the increase of the initial solid concentration for the evaluated scenario.

5. CONCLUSION

The difference in the grain size distribution curves of the slurry solid content directly affects the formation of the filter cake, as it determinate if the addition of a coarse fraction is able or not to work as a filter for the slurry particles. In the tests executed, the addition of the uniform coarse material, CG, worked as a pre-filter for the material composed of fine particles (FG material), but not to the natural material, NG. It occurs because the framework formed by the coarse material retained by the geotextile was not capable to retain NG small particles.

These results according to the expected behavior considering Terzagui's filtration requirements indicated in Table 1, even though this proposal has been made to porous media filtration and no to particles in suspension. The coarse material meets the filter requirements for material FG but do not meet the second requirement for the material NG, even if the requirement is not met by a small margin.

Also, the diameter of the solid particles has influence in the filling phase, smaller particles result in less permeability in the filling phase, but this behavior does not propagate to the dewatering phase, possibly due to the fact that there has been a significant passage of fines.

A portion of 3% by a solid mass of CG was able to reduce the permeability of the system (dewatering phase duration is three times longer) and increase the solid's retention.

For sludges composed only of FG, the increase in initial solid concentration does not improve the filtration efficiency or the retention capability.

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