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Evaluation of the granulometry of filter materials for earthworks

Avaliação da granulometria de materiais de filtros para obras de terra

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Abstract: The percolation of a fluid through soil is related to the ability of an earthwork to relieve stresses. Certification of the classical criteria of permeability and retention in dam filters allows for the analysis of filtration mechanisms, fine particle clogging, particle infiltration, and transport. This study highlights the differences in percolation behavior for different base materials, with soil 1 being more than 60% clay, soil 2 with predominantly silt, soil 3 characterized as sandy, and mining tailings, each tested with two types of filter material, having sandy fractions of 90% and 60%. The tests for permeability, combined percolation, and suspended and total solids, along with the analysis of material interactions, made it possible to observe, among other discussions, that the use of a more open granulometry as a filter material did not satisfy the retention criteria for base materials with silty characteristics, but when combined with base materials having high clay fraction, their larger voids did not favor the transport of particles. It was concluded that the better graded sand is suitable as a filter material for the drainage of earthworks that use any of the four types of base materials studied, under ideal design practices.

Keywords: Filter; Drainage; Transport of particles.

Resumo: A percolação de um fluído através do solo está relacionada à capacidade de aliviar as tensões de uma obra de terra. A certificação dos critérios clássicos de permeabilidade e retenção em filtros de barragens permite análise de mecanismos de filtragem, colmatação dos finos, infiltração e carreamento de partículas. Assim, esta pesquisa traz a diferença do comportamento de percolação em diferentes materiais base, sendo solo 1 com mais de 60% de fração argilosa, solo 2com predominância de silte como porção fina, solo 3 com característica arenosa, e rejeito de mineração, para dois tipos de material filtro, com 90% e 60% de fração de areia. Dada a realização de ensaios de permeabilidade, percolação combinada, sólidos em suspensão e totais, análises das interações dos materiais permitiram observar, dentre demais discussões, que a utilização da granulometria mais aberta no material filtro não satisfez o critério de retenção dos materiais base com características siltosas, mas quando combinada com materiais com alta fração argilosas, seus maiores vazios não favoreceram o carreamento de partículas. Concluiu-se ser adequada a areia melhor graduada como material filtro para drenagem de obras de terra que utilizem algum dos quatro tipos de materiais base estudados, diante das práticas ideais de concepção.

Palavras-chave: Filtro; Drenagem; Carreamento de partículas.

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1. Introduction

Size calculations for earthworks, such as foundations and retaining walls, involve soil parameters that vary mainly due to their composition and state. Considering saturated study conditions, the application of stress to wet soil creates the pore pressure, which can be dissipated through an increase in stress in the soil. In most situations, this is responsible for ruptures and collapses in earthworks.

In the case of dams, the degree of conservatism adopted caries from project to project. Generally, this design definition takes into account the degree to which infiltration occurs within the massif, and this infiltration is controlled by the presence of filters and drains, by the use of free-draining rockfill in the embankment, and by control of the foundations through backfilling, drainage, and cuts (FELL et al., 2005).

The first widespread drainage sizing study was proposed by Terzaghi in 1926, who defined ideal values for the correlation between the granulometric percentages of the filter material and the base, in order to guarantee permeability and stability of the filters and their drainage compositions. Determining the ideal particle size for the filter material guarantees water percolation without erosion, particle loading, clogging, or piping, as well as the acceptable particle size for the filter material.

Currently, with projects being implemented with new objectives, applications, and technologies, such as the stacking of tailings in mining, there is much discussion about how appropriate the optimization of the classic criteria in projects is, since they continue to be in evidence and widely used.

It is understood that more than one technically suitable filter material can be adopted for the same base material, and vice versa. With this in mind, this study proposes a comparative analysis of the filtration efficiency of four different base materials with two types of filter material. This is because the definition of the permeability relationships between the filter and the base material makes it possible to discuss drainage efficiency, whether particles are carried away by the flow, whether there is a tendency for the filter material to clog, and also how the permeability of each base soil behaves when in contact with different filters.

2. Methodology

The base material, or protected material, is the material that makes up the structure and is in direct contact with the drainage filter. This study used three materials of natural origin, collected at the Viçosa/MG Campus of the Federal University of Viçosa (UFV), called Soil 1, Soil 2, and Soil 3, plus a fourth material, called Tailings, that originated from iron ore extraction activities, provided by the mining company CSN (*Companhia Siderúrgica Nacional*) through a research partnership with UFV. CSN Mining's operational and production complex is located in the Iron Quadrangle in the state of Minas Gerais.

For the filter material, the sand, marketed as "medium," was purchased in the city of Viçosa/MG, with the first type being sand directly as supplied, referred to as Natural Sand, and the second type being sand characterized as poorly graded sand, obtained by sieving, and made up of the portion passing through the 4.75 mm sieve and retained by the 1.18 mm sieve, called Coarse Sand. Figure 1 illustrates the materials described and used.

Figure 1 – Photos of the materials used: Soil 1, Soil 2, Soil 3, Tailings, Coarse Sand, and Natural Sand.
Source: Authors (2022).

The first method used by the study includes characterization tests, namely a compaction test in accordance with NBR (*Norma Brasileira*) 7182 (ABNT, 2020), which determines the optimum humidity (w_{ot}) and maximum dry specific weight ($\gamma_{d,max}$) of the samples tested; a granulometry test in accordance with NBR 7181 (ABNT, 2017); and a specific mass of solids test (ρ_s) in accordance with NBR 6458 (ABNT, 2017).

The guidelines proposed by the USDA SCS (United States Department of Agriculture Soil Conservation Service) in 1986, revised by the NRCS (Natural Resources Conservation Service) in 1994 and in line with the ICOLD (International Commission on Large Dams) in 1994, were followed in order to determine the granulometric range for the filter material, which are commonly interpreted as criteria that are sufficiently suitable for engineering and dam filter projects. They are available in Fell et al (2005, p.361).

The classic sizing criteria are based on the behavior of flows through granular materials, the first of which is the retention criterion, stability criterion, or piping criterion, which defines a relationship where the dimensions of the voids between the grains of the filter are small enough so that the particles of the protected material cannot infiltrate. The second is the permeability criterion, which defines a relationship where the filter has sufficient hydraulic conductivity to guarantee the expected flow conditions. After Terzaghi (1926), several complementary studies were published, including those by the USBR (United States Bureau of Reclamation) (1977) and by Sherard and Dunningan (1985 and 1989).

The flowchart in Figure 2 illustrates the stages of the methodology adopted, which includes tests to determine the coefficients of permeability at constant load, using the test published by Caneschi (2012) for base materials, and the NBR 13292 (1995) standard for filter materials. Tests to determine percolation in combined materials; individual quantification of the suspended solids present in the fluid passing through the percolation test, similar to the 2540D test (APHA - American Public Health Association, 1998); and a determination of the total solids in the fluid that resulted from washing the filter material after it had been removed from the percolation test, according to 2540G (APHA, 1998), were also carried out.

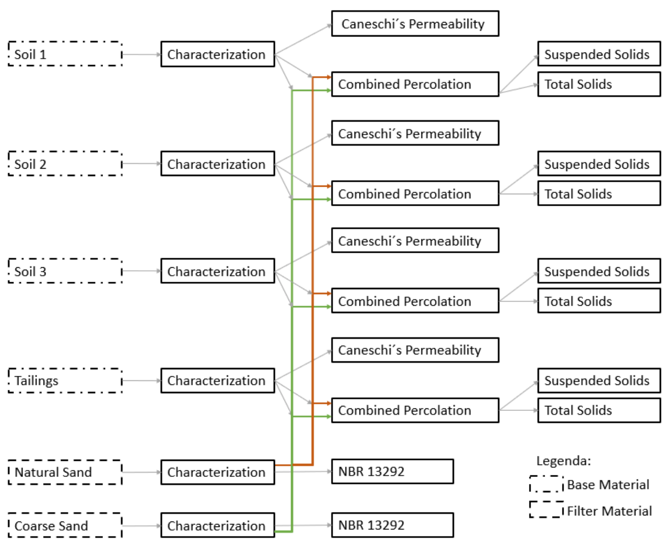


Figure 2 – Flowchart of the testing steps and how they are associated.
Source: Authors (2022).

Of the non-standardized tests carried out during this study, the permeability test with the Caneschi apparatus was used to determine the permeability of Soils 1, 2, 3, and the Tailings. The details of the test can be found in Caneschi (2012). In this study, it should be noted that the fluid selected for percolation through all the test specimens was distilled water, all test specimens were assembled with static compaction and obeying a degree of compaction varying from -2% < 99% > +1% with humidity varying up to 2% of the optimum characteristic value, and that a minimum of three repetitions were carried out for each of the four base material types selected.

The percolation test with combined materials was proposed to analyze the seepage flow and permeable parameters of two materials arranged in direct contact within a permeameter. The test collects data on the fluid outflow of a system with base material and filter acting simultaneously. Using the same principle as Caneschi (2012) and adapting the sizes of the test specimen and interface cell to enable direct deposition of two materials, the volumetric fluid capacity available was increased to be able carry out a complete test at high flow rates.

In this test, the degree of compaction was set at 60% ± 2%, with humidity varying up to 2% from the optimum value (w_{ot} ± 2%) for the protected material, in order to maintain cohesion and consistency balanced against a large amount of percolating voids, and humidity of 95% ± 2% for the filter material, dried in an oven. The filter material was washed before being molded, in order to remove the fine material, so that the presence of fines in the sand after percolation would indicate loading of particles from the base material. As for the percolation test pressure, the hydraulic load applied was gravitational with a gradient equivalent to a value of 9.61, with negligible pressure drop in the filter material. The downward flow of water was adopted in order to facilitate infiltration of the particles into the filter material, with gravity acting in favor. Three replications were proposed for this test for each combination of materials. All of the percolated fluid was collected and weighed, its temperature was measured and the total duration was recorded, so that it could be later used in the suspended solids test. The material used for the total solids test was obtained by washing the filter material following the combined percolation test, in order to quantify the amount of fine material retained inside the filter.

With the help and technical instruction of LESA, UFV's Sanitary and Environmental Engineering Laboratory, the suspended and total solids tests were carried out in accordance with the American Public Health Standards, APHA 1998. The suspension test used a glass fiber filter (GF/C 47 mm x 1.2 um) and a filtering volume of 3 liters per period. A #200 sieve (0.75 mm) was used to wash the filter material extracted from the inside of the specimen at the end of the combined percolation test, collecting approximately 2 liters of residual fluid, for the total solids test, conducted by drying the material completely in an oven at 110°C.

Further details on the methodology used are available in the master's thesis of Perim (2023).

3. Results and discussion

In accordance with Brazilian standards, Table 1 shows the characterization data obtained from Soil 1, Soil 2, Soil 3, the Tailings, the base materials, and the respective natural and coarse sands (the filter materials). The data obtained showed a high percentage of clay present in Soil 1, a predominance of fine silt in Soil 2, a large sandy portion in Soil 3, and Tailings with a silty-sandy composition. It is important to note that, despite the use of soil mechanics theories, which are indicated for soils of natural origin such as Soils 1, 2, and 3, they may make comparative and concrete analysis of the Tailings difficult. Because it is a sediment that has undergone a lot of manipulation during mining, such as excavation and filtering, its characteristics and behavior may be altered. Comparing the two filter materials, a difference of more than 30% in the portion of sand is noted.

Table 1 – Base and filter material characterization results.

Characterization results						
Characterization	**Soil 1**	**Soil 2**	**Soil 3**	**Tailings**	**Natural Sand**	**Coarse Sand**
Clay (%)	66	5	5	11	0	0
Silt (%)	11	42	24	58	0	0
Sand (%)	23	53	68	31	91	57
Gravel (%)	0	0	3	0	9	43
ρ_s (g/cm³)	2.87	2.59	2.66	3.27	2.684	2.665
w_{ot} (%)	31.00	23.13	15.00	12.30	-	-
$\gamma_{d,max}$ (kN/m³)	13.93	15.68	17.17	20.90	-	-

Source: Authors (2023).

The granulometric curve for the base material is crucial for calculating the filter sizing criteria. It is used to define the ideal particle size range for a filter material to meet both the permeability and retention criteria. Figure 3 below shows the granulometric curves of the base and filter materials used in this study. Comparing the soils of natural origin, it can be seen that Soil 1, shown in black, is mostly fine, which is the opposite of Soil 3, shown in blue, which is predominantly sandy. Soil 2, shown in orange, has an intermediate grain size divided almost equally between fine and sandy. The particle size curve for the base material of manufactured origin, Tailings, shown in green, has the worst gradation characteristics. The grain size of the coarse sand is highlighted in pink and the natural sand in gray. The percentage difference in the particle size curves for the two is consistent with the idea that natural sand is better graded and has more fines filling its voids.

The appropriate particle size ranges were defined for each of the base materials in the study, using this characterization data. Figure 3 also shows the grain size ranges calculated for the protected materials. The range defined for Soil 1, Soil 2, and the Tailings was the same and falls within the limits highlighted with continuous red lines. The range calculated for

Soil 3 is shown in the graph below by red dashed lines. Applying the grain sizes of the sands proposed for the filter materials to the dimensioned ranges, it can be seen that neither is completely included. The coarse sand fell within the range at the top of the curve, while the natural sand fell within the range at the bottom of the curve, as can be seen in the graph.

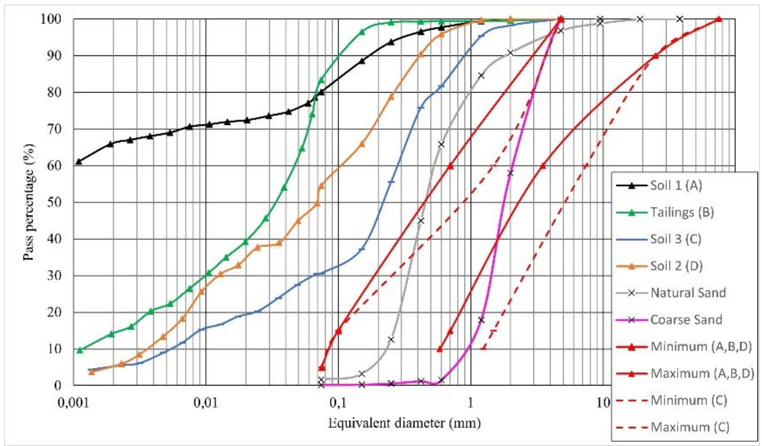
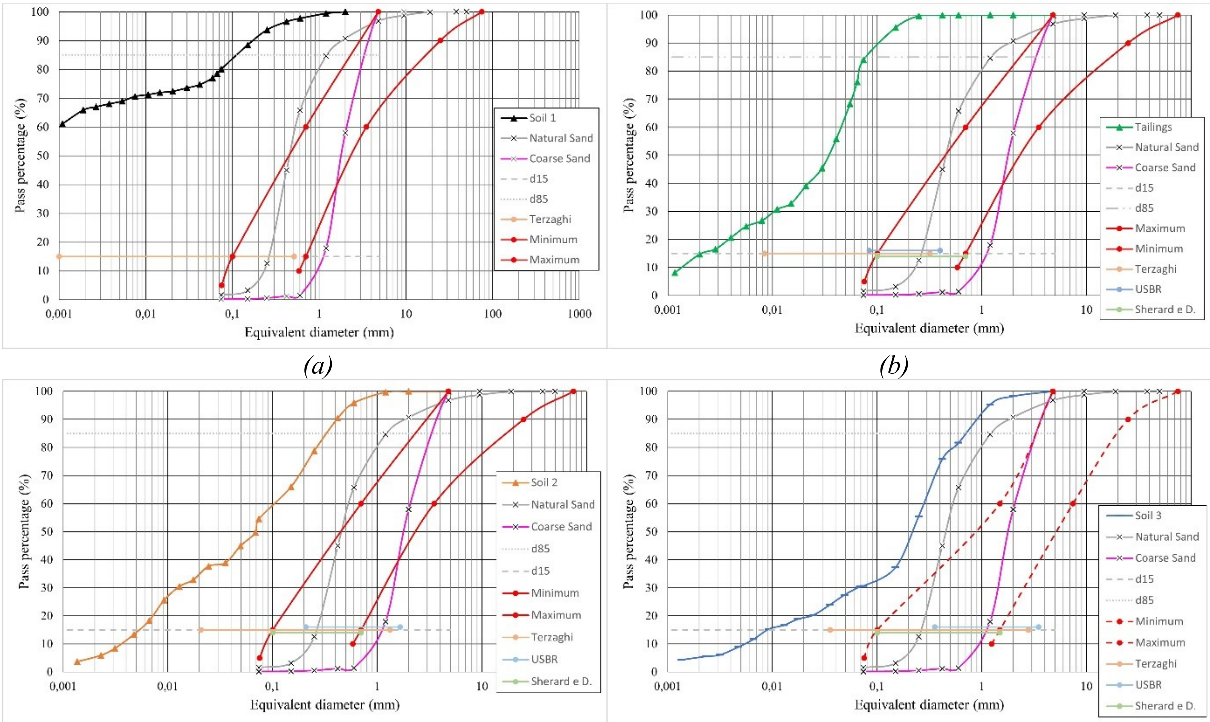


Figure 3 – Granulometric curve of the materials and size intervals.
Source: Authors (2023).

For sizing, a possible interval is defined which comprises a range of acceptable values for the equivalent diameter of a sieving mesh, so that only 15% of the material will be able to pass through it (D15). Figure 4 shows the particle size curves for each material with the sizing analyses proposed by Terzaghi, USBR, and Sherard and Dunningan. Graphs a and b in Figure 4 show that natural sand is the ideal material for Soil 1 and Tailings, while natural sand or coarse sand could be used for Soil 2. For Soil 3 (Figure 4d), coarse sand covers all of the intervals proposed by the design criteria, while natural sand is not suitable for the possible D15 values established by the USBR.



(a) *(b)*

(c) *(d)*

Figure 4 – Graphs of the sizing intervals for the base materials with filter materials (a) Soil 1 (b) Tailings (c) Soil 2 (d) Soil 3.
Source: Authors (2023).

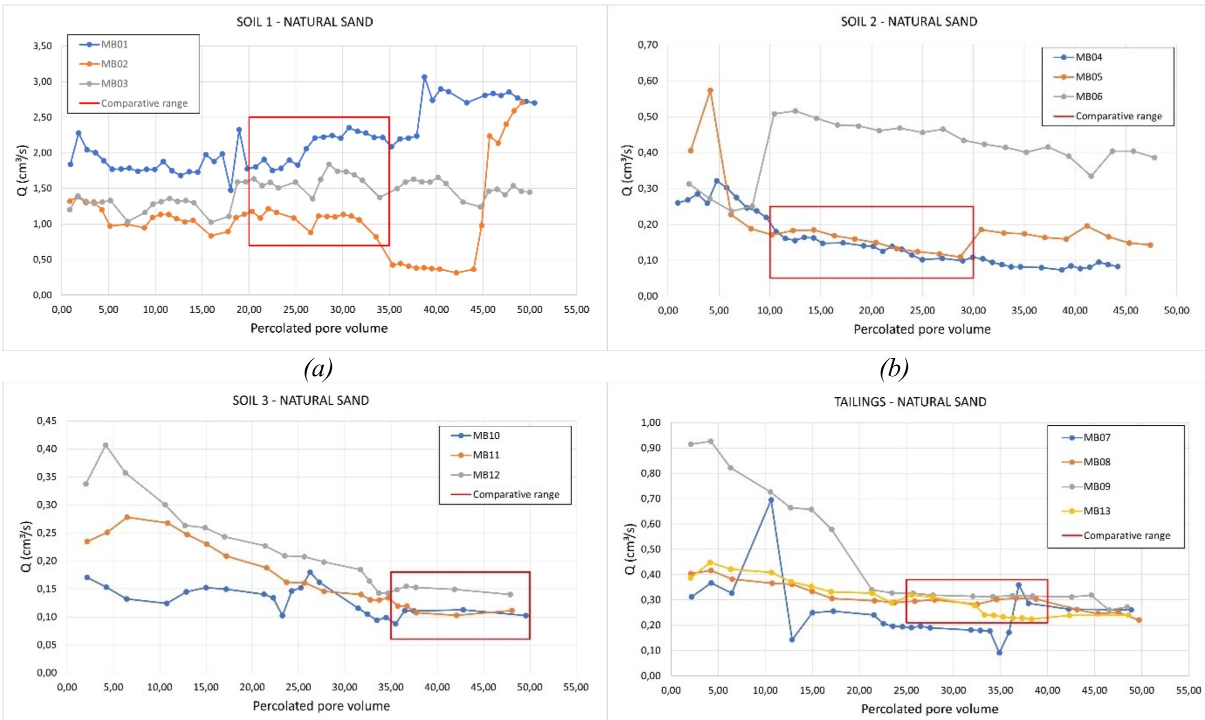
The permeability test for each respective base material, carried out four times, returned an average k_{20} value, the coefficient of permeability at 20°C, of 4.52 x 10^{-8} cm/s for Soil 1, 3.91 x 10^{-7} cm/s for Soil 2, 3.29 x 10^{-6} cm/s for Soil 3, and 2.31 x 10^{-6} cm/s for Tailings. Correlation of the permeability values found with the granulometric fractions of each material obtained during the characterization shows that, although Soil 2 has a sandy fraction more than 20% higher than that of Tailings, the permeability of the Tailings was higher than that defined for Soil 2. This would not be the case if it were based on classical soil mechanics theory, since the presence of sand in soil is directly linked to its capacity for fluid percolation. There are therefore other variables that influence the determination of the hydraulic conductivity of a manufactured material such as tailings. It is also possible to correlate the low k_{20} value of Soil 1 with its high clay content, as clays are recognized in geotechnical circles as fine minerals with a high particle surface area for their mass, meaning that their particles interact strongly. Soil 3, which has the highest permeability coefficient, has a high percentage of sand in its composition, which is a non-cohesive granular soil.

The average coefficient of permeability for natural sand was determined to be 8.55 x 10^{-3} cm/s, and for coarse sand it was determined to be 2.59 x 10^{-2} cm/s. Therefore, natural sand, which contains a higher portion of finematerial in its granulometry, had a lower hydraulic conductivity than coarse sand.

The flow rate through the pores of the specimens determined by the percolation test is shown in the following graphs. Figure 5 shows the individual developments of the base materials with natural sand and Figure 6 shows the same materials combined with coarse sand. The first thing to notice, when looking at the plotted graphs of the tests carried out, is the greater variability in the data for the tests with natural sand than with coarse sand.

The behavior of Soils 2 and 3, as shown in the graphs in Figure 5, can be understood as a greater variation at the start of percolation followed by a tendency for the data to become uniform. It was therefore considered that the beginning of the test included the saturation interval of the samples, with their percolation values approaching each other as the volume increased. The combination with Soil 1, on the other hand, did not show a peak decrease like the others, a fact that can be explained by the high concentration of clay and its low hydraulic conductivity capacity. The graph for Soil 2 with natural sand in Figure 5b shows a considerable discrepancy observed mainly in MB06 when reaching 10 percolated pore volumes.

At the same time, a change in the positioning of the collection hose and an increase in the system's pressure drop were reported. The results obtained for the percolation flow rate in the Tailings combined with natural sand showed an inconstancy in the initial phase that be attributed to the anisotropy of the material, the saturation phase, and the rearrangement of the particles until the values began to stabilize.



(a) *(b)*

(c) *(d)*

Figure 5 – Graphs of percolation combined with natural sand (a) Soil 1 (b) Soil 2 (c) Soil 3 (d) Tailings. Source: Authors (2023).

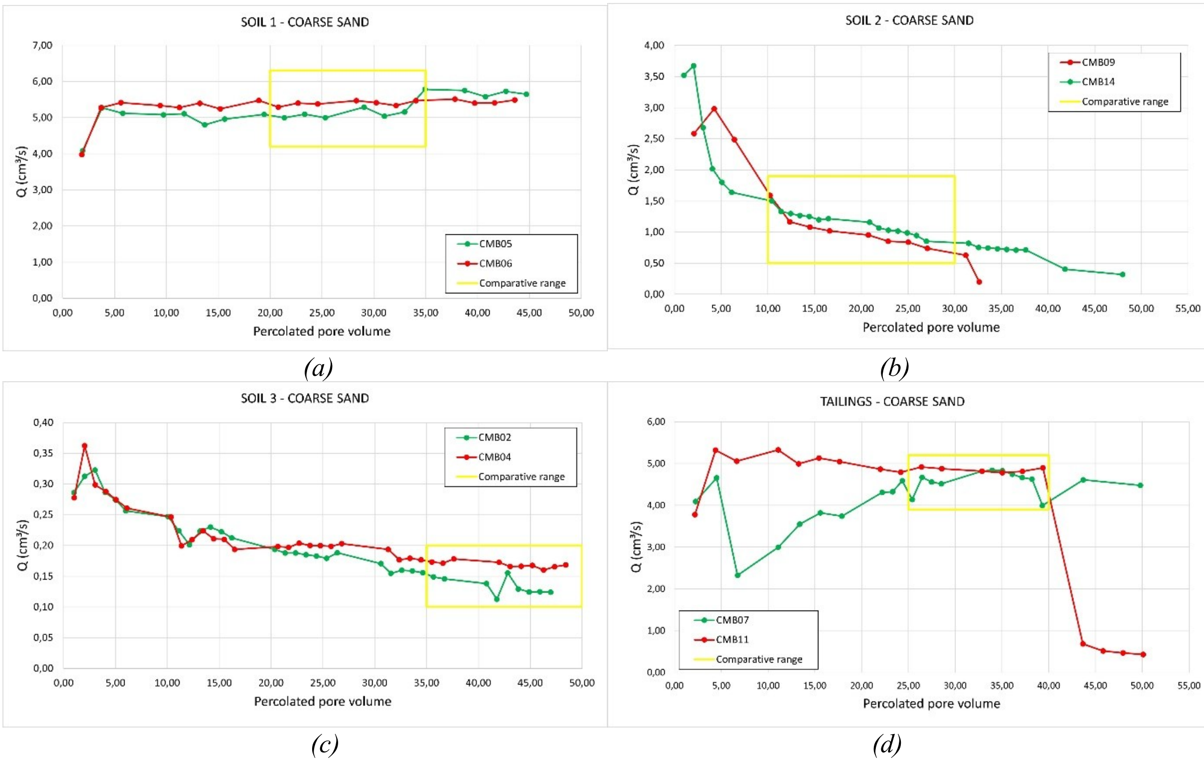


Figure 6 – Graphs of percolation combined with coarse sand (a) Soil 1 (b) Soil 2 (c) Soil 3 (d) Tailings. Source: Authors (2023).

Both when combined with natural sand and with coarse sand, the percolation flow rate of Soil 1 was fairly stabilized and did not undergo sudden changes, as shown in Figure 6. The percolation curves for Soils 2 and 3 combined with coarse sand are also very similar to each other, and show a decreasing behavior followed by apparent stabilization, just as when tested with natural sand, which is characteristic of the saturation phase. As the test with Soil 2 progressed, the flow rate decreased, reducing fluid output to very near zero, suggesting that clogging may have occurred in the filter material due to possible obstruction of the percolation pores by particles that have been carried away. In a more comprehensive comparison of the combination with Soil 3, it is interesting to note that the total test time of the MB12 and CMB04 specimens was practically the same and their graphical behavior was also very similar. In the percolation test of the combination of Tailings and coarse sand, there was an inconsistency in the initial phase attributed to anisotropy and variations in the material, followed by a certain stabilization. Just before reaching the volume of 40 percolated pores, CMB11 suffered a sudden drop in flow. This behavioral change coincided with an interruption in percolation supplying water to the interface cell. At this point, the test specimen had a flow "freeze," i.e. the water stood still inside the test specimen, and the drop in flow values that occurred after this episode, combined with the observation of greater settling of particles at the bottom of the container holding the percolated fluid, suggested that particle accommodation in the pores of the materials reduced the ease with which the fluid could flow.

For a comparative analysis of the percolation flow rates of the same base material with different filter material combinations, a comparative range of percolated pore volumes was defined and the average flow rates for each use of coarse sand and natural sand were calculated. Table 2 below shows the ranges and their average flow values.

Table 2 – Average percolation values for the base materials in their various combinations

Average percolation of protected materials			
Material	**Average range (VPP)**	**Natural Sand Q (cm³/s)**	**Coarse Sand Q (cm³/s)**
Soil 1	20 to 35	1.587	5.293
Soil 2	10 to 30	0.143[a]	1.090

Soil 3	35 to 50	0.122	0.152
Tailings	25 to 40	0.291*	4.715

*Q – percolation flow rate; VPP – percolated pore volume; * - average calculated from values of MB08, MB09, and MB13; [a] – average calculated from values of MB04 and MB05.*
Source: Authors (2023).

Comparing the values for Soil 1, the percolation flow rate is more than 3.5 cm³/s more in the specimens combined with coarse sand than in those with natural sand. In other words, the fluid percolated more easily when the filter material had a smaller grain size and larger voids. For the cases using Soil 2, there was a decrease in percolation flow when the combination used coarse sand as the filter material. This comparison reaffirms the previously proposed interpretation that the percolation pores of the coarse sand may have become clogged. The results for Soil 3 being practically the same support a similar interpretation of infiltration efficiency with both the use of natural sand and coarse sand as a filter material for an earthwork containing a material to be protected having similar characteristics. In the case of Tailings, the difference in percolation values reached nearly 4.5 cm³/s. The percolation flow rate in the test specimens using Tailings and coarse sand was significantly higher than that using natural sand.

Correlating the results with the granulometry of the materials, the soils with the greatest amount of fine material had greater difficulty percolating through the natural sand, which also had the greatest amount of fine material. As the fluid moved from the soil into the filter, fine particles must have been carried into the immediate contact area, forming self-filtering zones. When compared to the permeabilities found as a parameter for each soil in this study, the value of the average permeability coefficient for all of the soils increased.

The fluids resulting from the percolation tests were collected and conditioned approximately every five periods of percolated pore volume, so that they could be tested and the evolution of the presence of suspended solids being carried out of the filter system could be analyzed. In Figure 7 below, the collection intervals and their respective percolated pore volumes are shown individually.

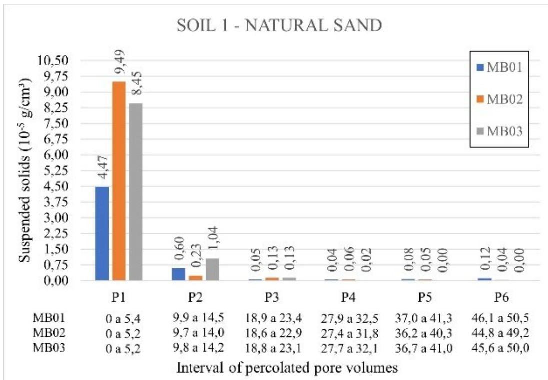
The suspended solids data is shown in Figure 7, with the solids concentration values for each test interval. Appendix A contains explanatory diagrams for each specimen, making it possible to quantify the suspended solids collection and percolation analyzed in each test.

The suspended solids concentration graph for Soil 1, Figure 7a,b shows considerably high values during the first volumetric interval of analysis, followed by a steep reduction reaching numbers close to zero. This behavior can be observed regardless of the filter material used in the combination. The difference is given in terms of the magnitude of the values. The combination of Soil 1 and coarse sand collected the fewest particles removed by the percolation of the fluid. This result is surprising given that this soil contains a large amount of clay, which is a fine particle, and that coarse sand has larger voids between particles, two factors that would make it easier for fine material to be carried into the pores of the filter material.

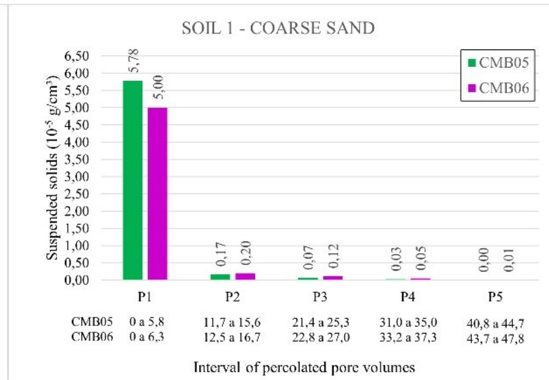
The comparison between the solids concentration values for Soil 2, Figure 7c,d, shows that the amount of solids carried by the fluid percolating through Soil 2 increased with coarse sand. The interpretation of CMB09 clogging in P4 is confirmed by the quantitative solids data. Analysis of the percolation data for this same period of percolated pore volume, in the case of CMB09, shows that the sharp decrease in flow rate occurred during the same interval in which the mass of solids increased.

With the use of coarse sand as a filter material in the test with Soil 3, Figure 7f, the results for solids present in the percolated fluid show that the particles were carried away in the first period of percolated pore volume. Compared to the results in Figure 7e, the use of natural sand as a filter material generated a more constant movement of particles. The more constant behavior, in this case, does not favor the settling of the particles in the pores and allows for a non-turbulent flow.

In Figure 7g,h, showing the results from tests on the Tailings, considerable suspended solids values can be observed due to the initial percolation and consequent washing of the particles. In period P4 of the Tailings with natural sand, an increase in suspended particles stands out in MB07, which is the most significant. In line with the percolation data, MB07 suffered a drop in flow followed by an immediate increase. One interpretation is that the pores were initially clogging, until the impediment to the flow dammed the fluid, generating a discharge that suddenly increased the energy applied to the percolation and expelled many particles that had been deposited in the voids, allowing the fluid to pass again. As for the sudden drop in flow, highlighted in CMB11, the percolation of the fluid through the system was carrying particles both from the base material to the filter material, as well as out of the cell. The volume of particles rearranged and moved was large, thereby causing obstruction of the pores, which abruptly reduced the flow rate. With this large quantity, larger particles may have been expelled, which were then detected in the suspended solids test.



(a)



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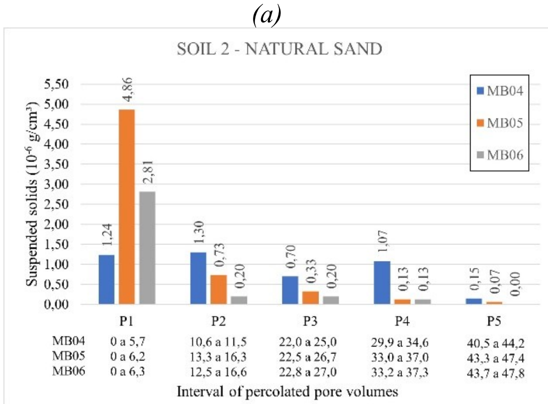

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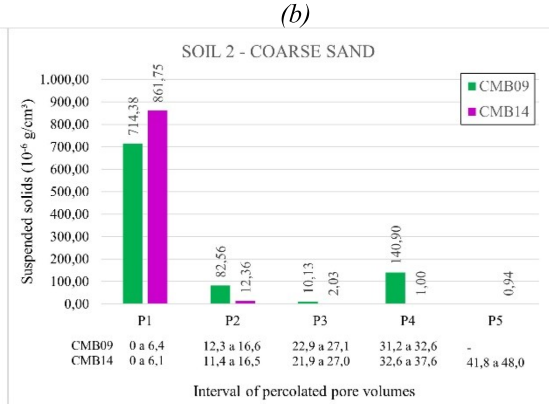

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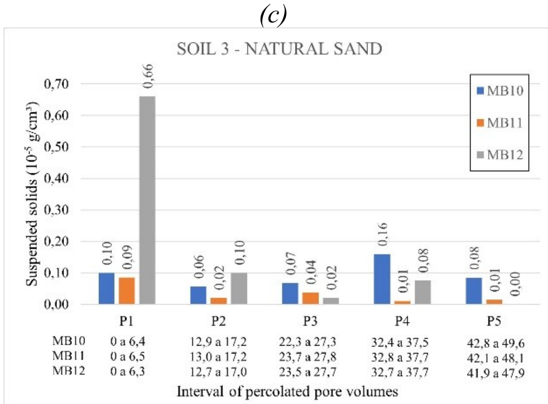
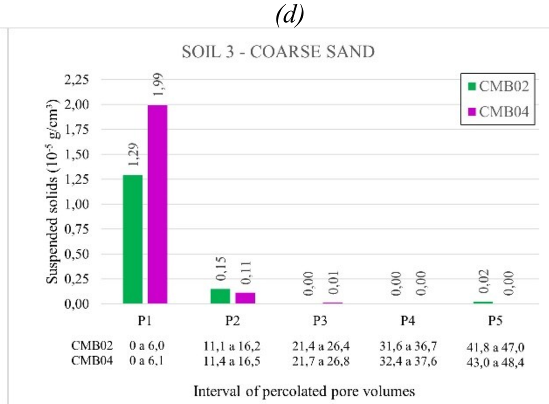
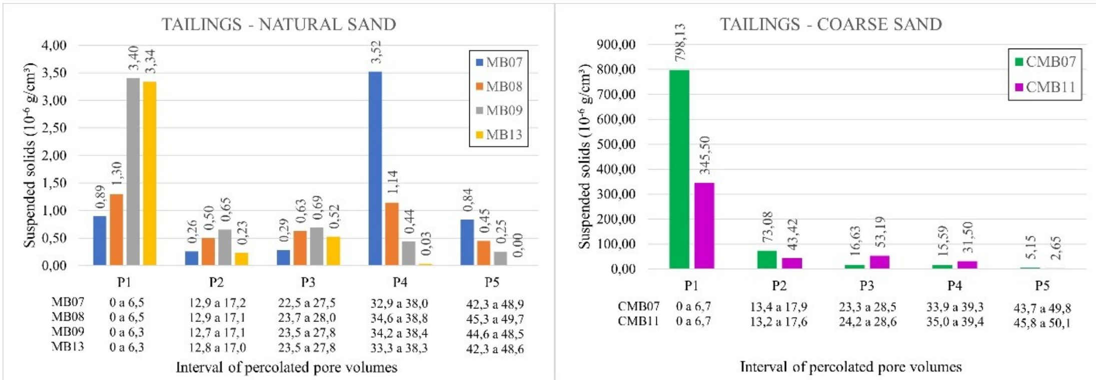


(e)



(f)



(g) *(h)*

Figure 7 – Graph of suspended solids for each volumetric interval of percolated fluid collected: (a) Soil 1 and natural sand, (b) Soil 1 and coarse sand, (c) Soil 2 and natural sand, (d) Soil 2 and coarse sand, (e) Soil 3 and natural sand, (f) Soil 3 and coarse sand, (g) Tailings and natural sand, and (h) Tailings and coarse sand.
Source: Authors (2023).

The total solids test was performed to measure the amount of fine particles that infiltrated into the filter material. Table 3 shows the quantitative data on the mass of particles that were inside the filter at the end of percolation. The values for natural and coarse sand were taken from the clean materials, for comparative purposes.

Table 3 – Total solids retained in the natural and coarse sand filter material samples.

Total solids retained in the percolated filter (g/cm³)						
Combination	**Soil 1**	**Soil 2**	**Soil 3**	**Tailings**	**Natural sand**	**Coarse sand**
Natural sand	0.000525	0.001133	0.000682	0.000914	0.000586	
Coarse sand	0.000683	0.005192	0.000828	0.013224		0.00034

Source: Authors (2023).

A greater quantity of fines carried into the filter material can be observed when coarse sand is used. The largest quantities of particles retained inside the filter material were found for Soil 2 and Tailings, consistent with the reduction in percolation flow rate measured in the test with combined materials. The photos in Figure 11 show the presence of particles inside the coarse sand making up the filter material during the removal of the mold, following the combined adapted permeability test, appearing as a pink coloration of the fluid present in the case of Soil 2 and a dark brown coloration in the case of Tailings. The change in coloration of the outlet fluid is an indication of particle transport, as its colors are similar to the colors of the respective base materials.

(a) *(b)* *(c)*

Figure 11- Photos of the removal of the coarse sand filter material from the mold with (a,b) Soil 2 and (c) Tailings.
Source: Authors (2023).

According to the study published by Neves and Caldeira (2021), using investigative microscopy on a drainage filter, fine sand and coarse silts were accumulated on the surface of the filter, medium to coarse silts and some clay were accumulated in the interior the filter, and fine to medium silts were suspended in the water passing through the filter. These characteristics were also observed in this study. The infiltration of silt particles into the filter was notable and in accord with the greater amount of voids in the material used.

4. Final Considerations

For permeability correlations, it is essential to understand the arrangement of particles and how the fine, medium and coarse portions interact. Despite the considerable difference in the granulometries of Soil 1, Tailings, and Soil 2, the granulometric range indicated for the filter material was the same. This occurred because the sizing limit values depend on adjustments and decision-making based on practical or design justifications, such as the adopted uniformity coefficient, for which the NRCS indicates only a maximum limit value of $C_u \leq 6$. These adjustments are normally only adopted in cases of extensive knowledge, because they directly influence parameters such as the uniformity coefficient of the filter material and consequently the efficiency of the filtration mechanisms.

Correlation of the percolation flow results with the protected characteristic granulometries, showed that it was more difficult for the fluid to pass through the base materials with a greater quantity of fine particles, when in contact with well-graded sand. It is possible to interpret that, as the fluid moved from the base to the filter, fine particles from the material are transported to the immediate contact area, forming self-filtering zones.

If the percolation flow rate in the combined materials is compared with the measurements to define the permeability parameters for each protected material in this study, the value of the average flow coefficient was higher in all cases that were in contact with the filter. Determining factors such as the degree of compaction of the base material adopted during preparation for the test were linked to the behavior of the percolation flow rate, approximately 60% in the combined test and 99% in the permeability test. These factors are also linked to the emergence of the filtration mechanism, where a distribution of fines occurs in the voids of the immediate base-filter contact zone, forming preferential paths for the passage of the fluid. The contact of the protected material with a material of different granulometry, having a greater volume of voids and lacking cohesion, facilitated the percolation of the fluid. Any sudden variation in the percolation flow rate directly influenced the quantity of particles present in the outlet fluid.

In the data from the solids study, the fine portion of the sandy soil, characteristic of Soil 3, made up only a small portion of the percolated fluid and the solids retained inside the filter material. Even so, the data for total solids are greater than those in suspension, suggesting that transport of fines occurred from the base material, just enough to form the self-filtering zone. Soil 1, which is predominantly clay, did not have a marked indication of particle transport either to the interior of the filter material, as detected in the total solids test, or in suspension in the water passing through the combined percolation system. The Tailings and Soil 2, both of which are materials with a high silt content, presented particle transport behavior both to the interior of the filter and in suspension in the outlet fluid. These behaviors were observed when using both filter materials, but with different intensities.

Finally, considering the analyses of both fluid percolation and solid particle retention, natural sand, a material within the granulometric range of the D15 criteria proposed during the sizing, performed satisfactorily overall. In the individual scenarios, only natural sand, i.e., well-graded sand, was effective as a filter material for Soil 2 and for Tailings. Both sands could serve as filter material in the cases of Soil 1 and Soil 3. However, for Soil 3, natural sand proved to be more suitable, because with its use there were fewer solid particles suspended in the collected fluid. For Soil 1, the use of coarse sand proved to be more efficient, both by offering greater percolation and lower particle transport. In contrast to the results expected in the study proposal, Soil 1 with a high percentage of clay, more than 60%, had almost no particle transport in the percolation fluid and developed a flow rate consistent with those dictated by the filter material used. This fact confirms the need for study and advancement in applied research on soil mechanics to support increasingly efficient and safe projects.

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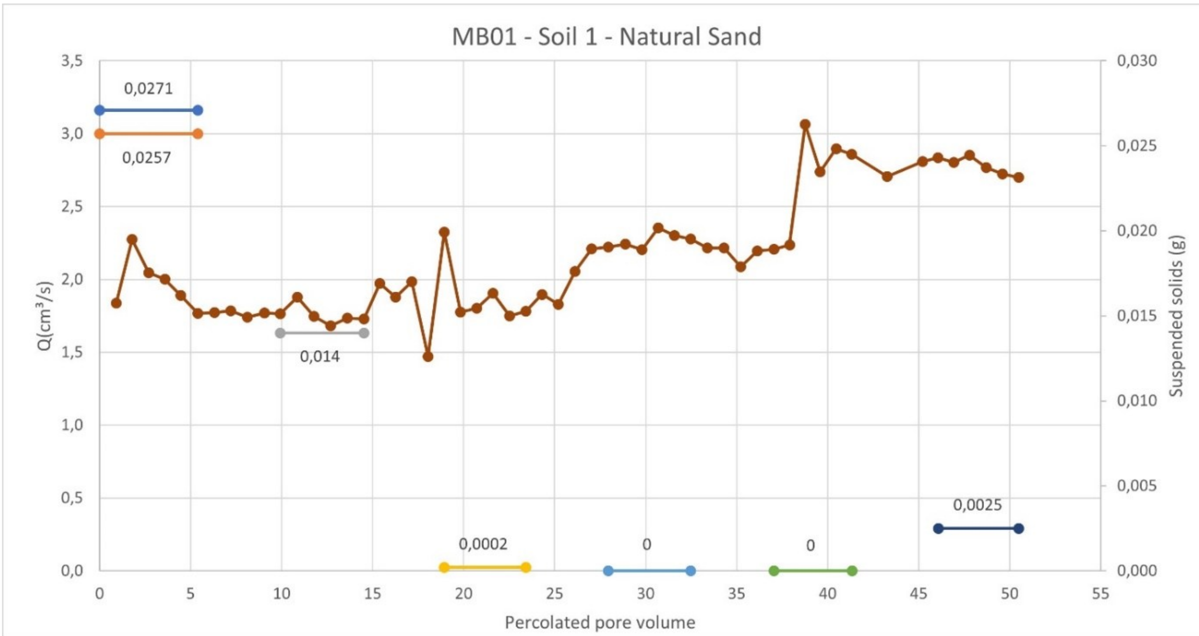
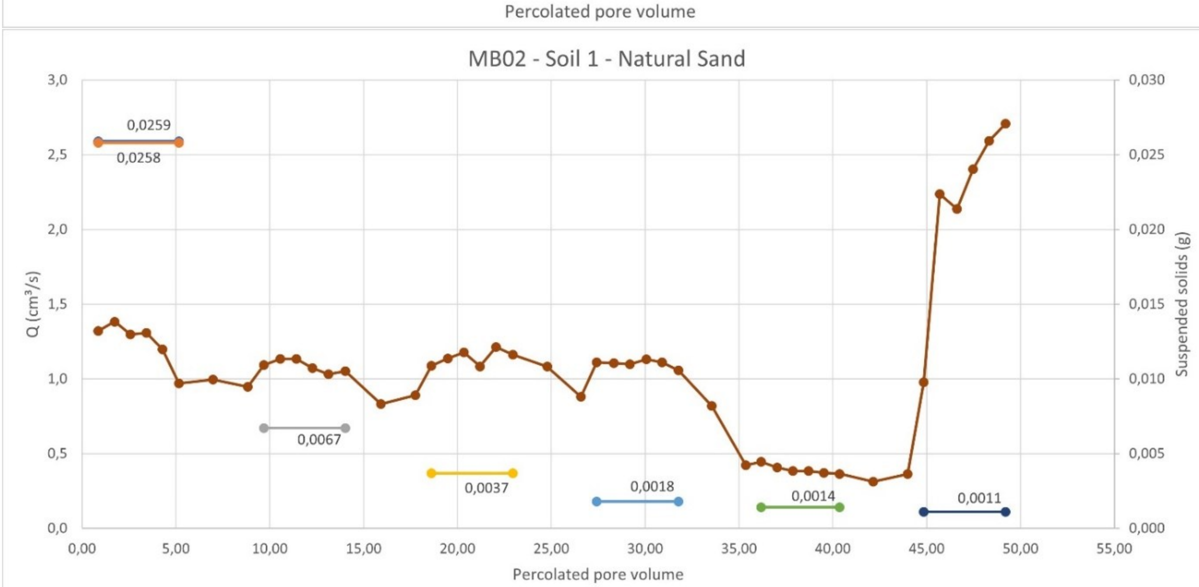
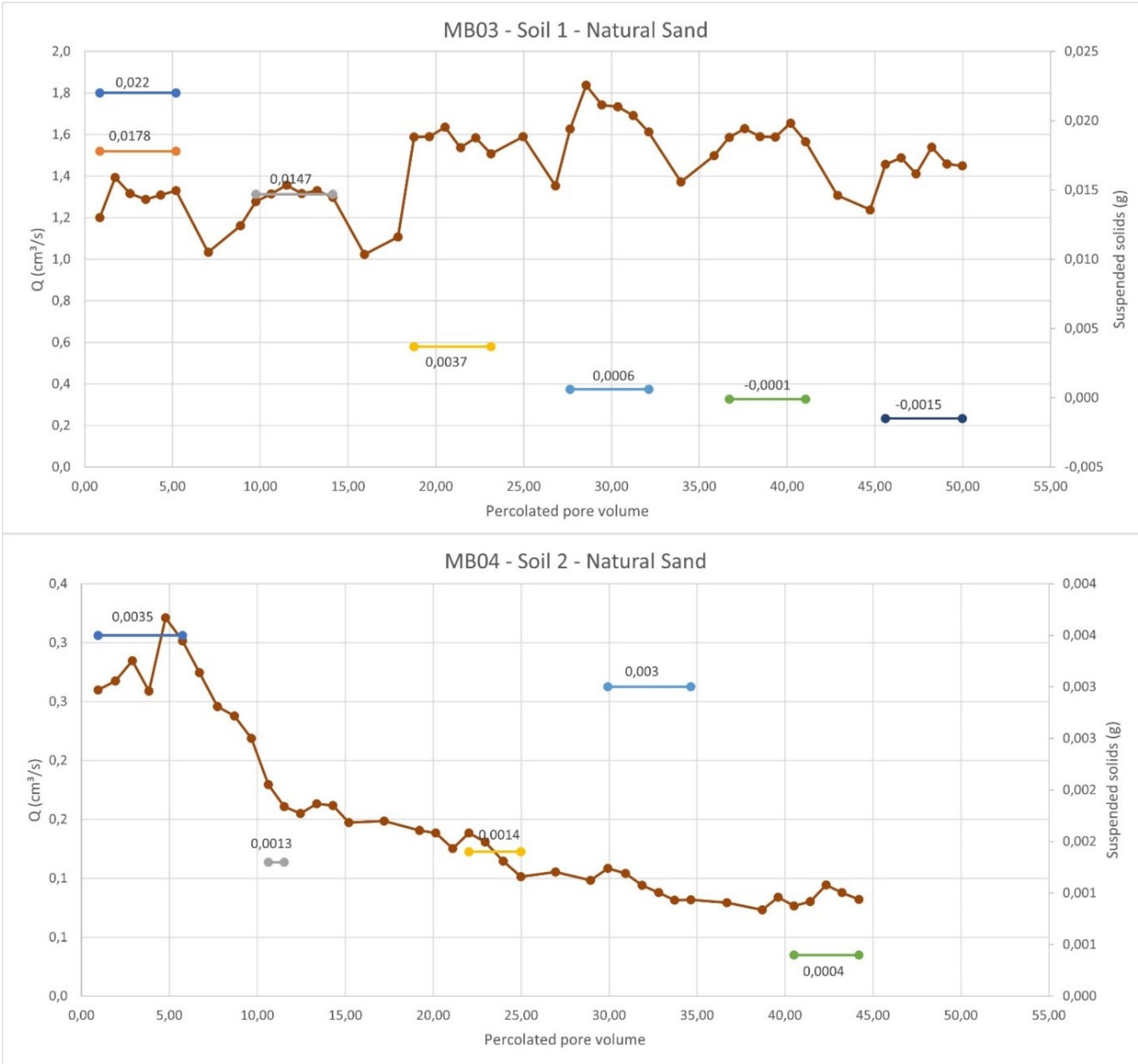
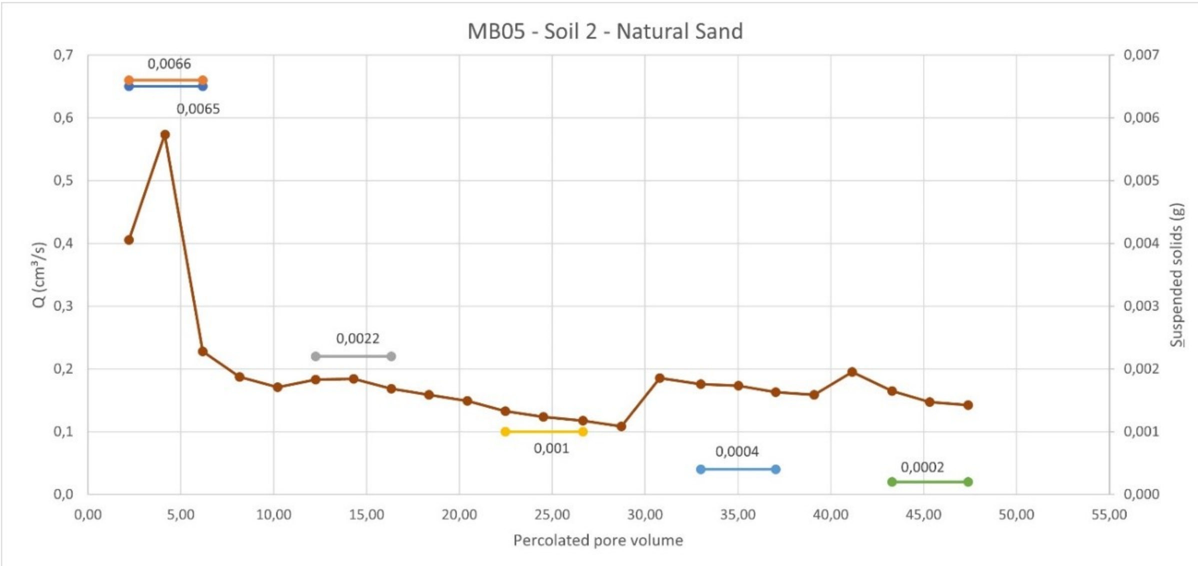
Appendix A

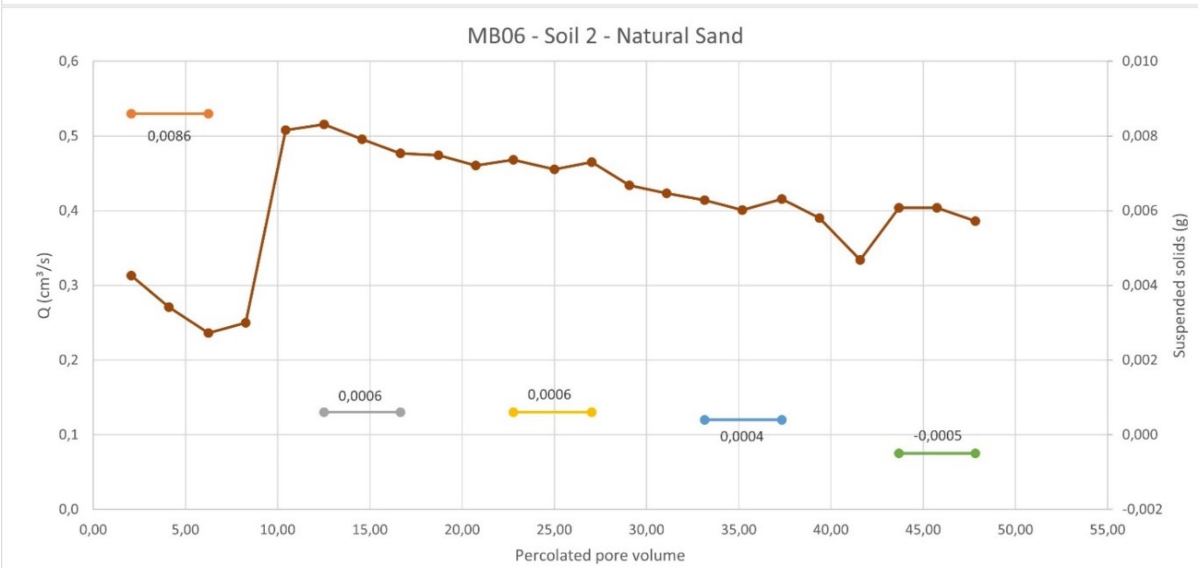
This appendix collects the graphs for each specimen subjected to the combined percolation test, showing the type of material in the title, the percolated pore volume as the horizontal coordinate, the suspended solids as the vertical coordinate on the right-hand side, and the percolation flow rate (Q) as the vertical coordinate on the left-hand side.

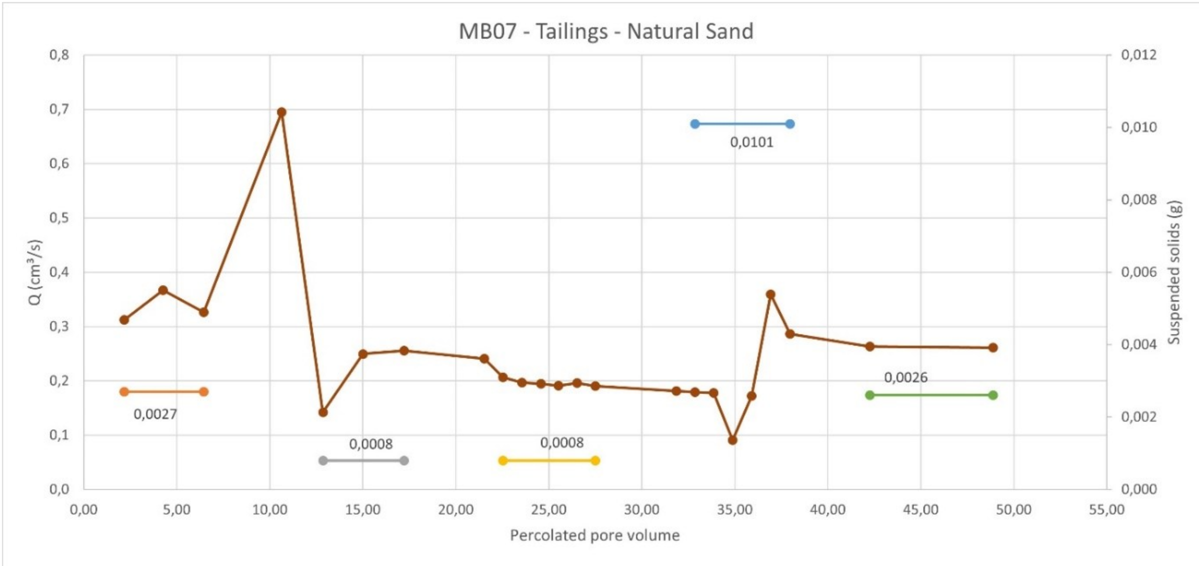


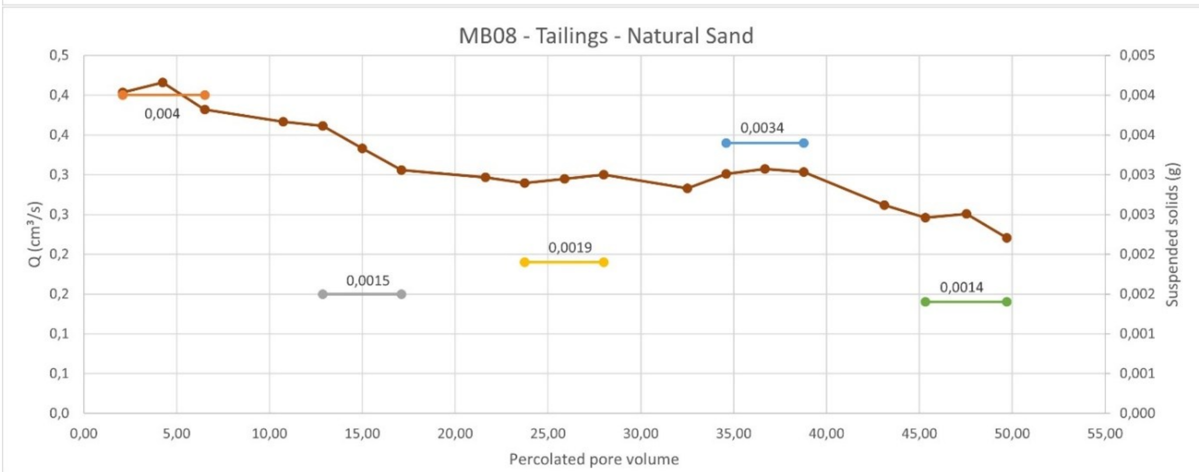


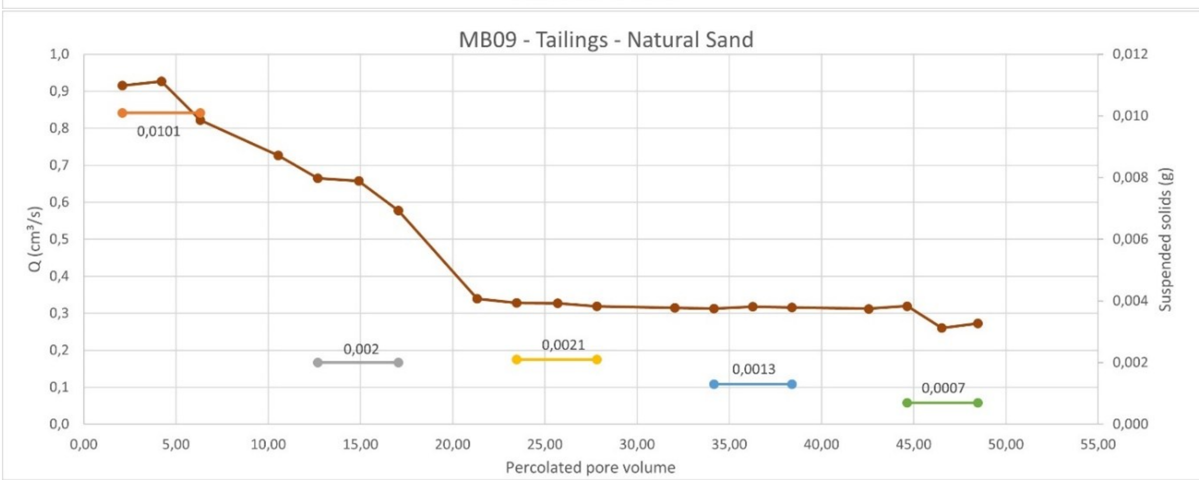

MB03 - Soil 1 - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,022
0,0178
0,0147
0,0037
0,0006
-0,0001
-0,0015
MB04 - Soil 2 - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0035
0,003
0,0013
0,0014
0,0004

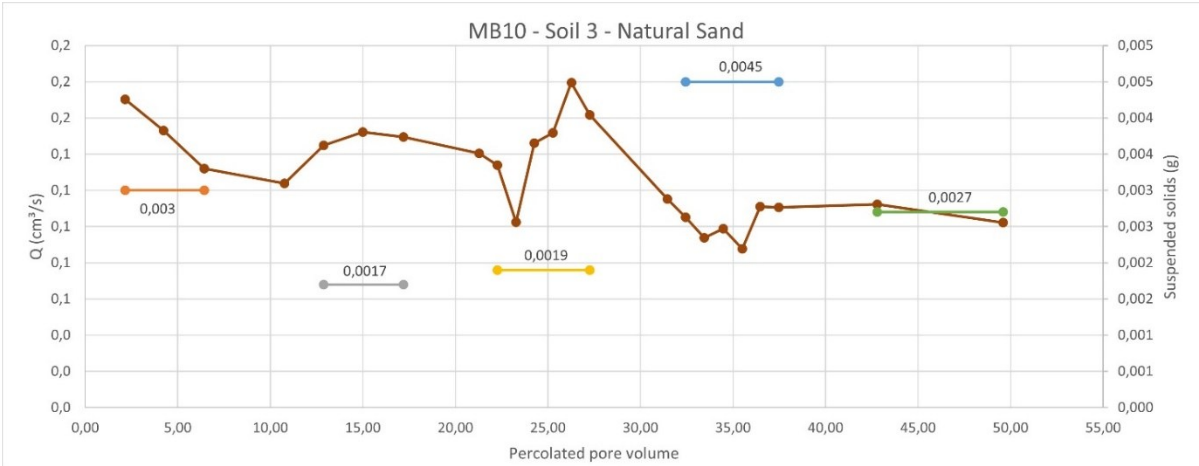

MB05 - Soil 2 - Natural Sand
0,0066
0,0065
0,0022
0,001
0,0004
0,0002
Q (cm³/s)
Suspended solids (g)
Percolated pore volume

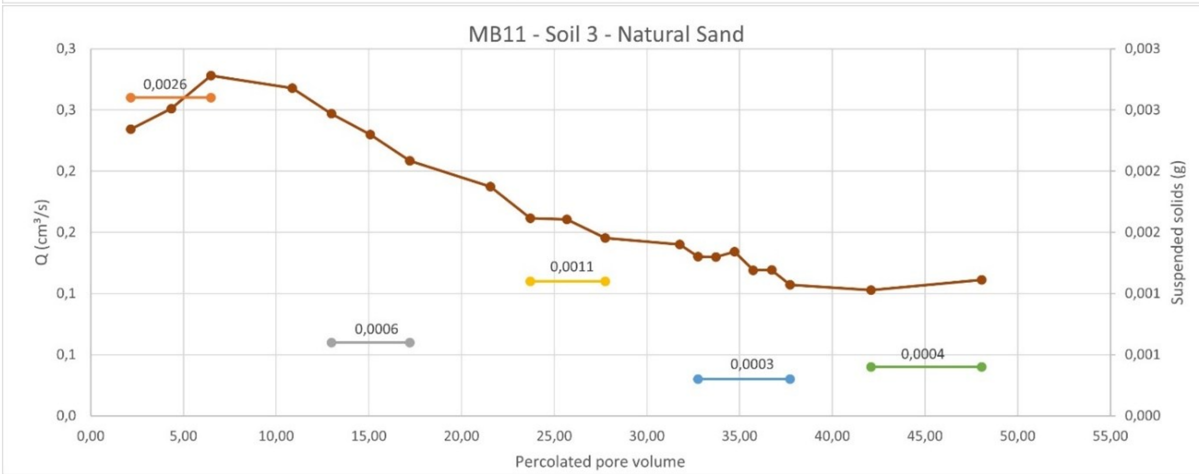

MB06 - Soil 2 - Natural Sand
0,0086
0,0006
0,0006
0,0004
-0,0005
Q (cm³/s)
Suspended solids (g)
Percolated pore volume

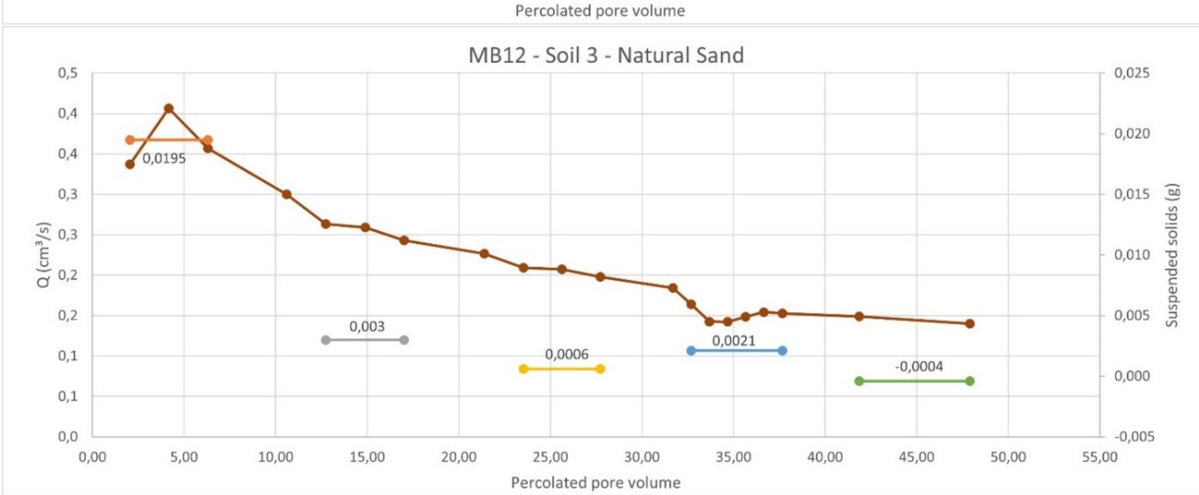

MB07 - Tailings - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0101
0,0027
0,0008
0,0008
0,0026
0,0 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8
0,000 0,002 0,004 0,006 0,008 0,010 0,012
0,00 5,00 10,00 15,00 20,00 25,00 30,00 35,00 40,00 45,00 50,00 55,00

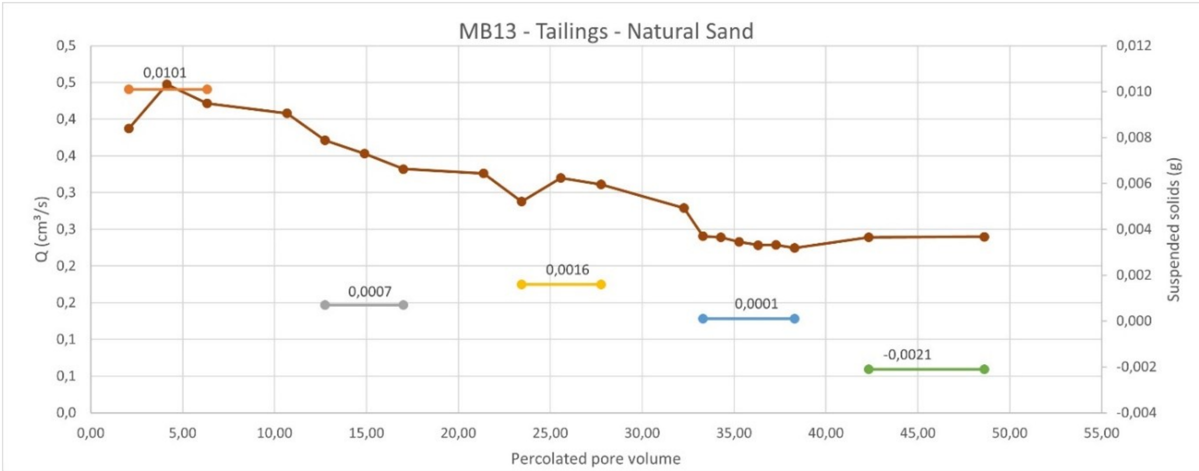

MB08 - Tailings - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,004
0,0034
0,0019
0,0015
0,0014
0,0 0,1 0,1 0,2 0,2 0,3 0,3 0,4 0,4 0,5
0,000 0,001 0,001 0,002 0,002 0,003 0,003 0,004 0,004 0,005
0,00 5,00 10,00 15,00 20,00 25,00 30,00 35,00 40,00 45,00 50,00 55,00

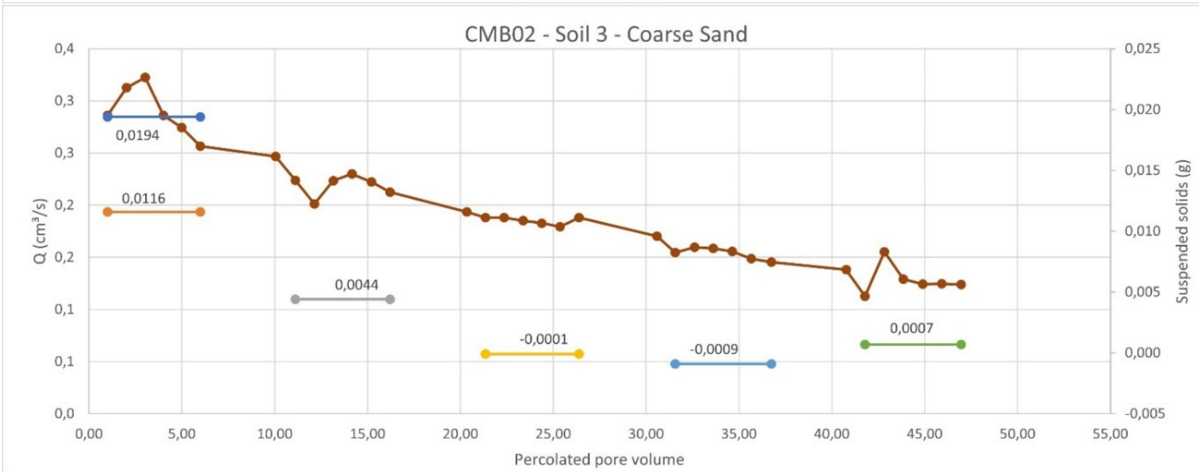

MB09 - Tailings - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0101
0,002
0,0021
0,0013
0,0007
0,0 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1,0
0,000 0,002 0,004 0,006 0,008 0,010 0,012
0,00 5,00 10,00 15,00 20,00 25,00 30,00 35,00 40,00 45,00 50,00 55,00

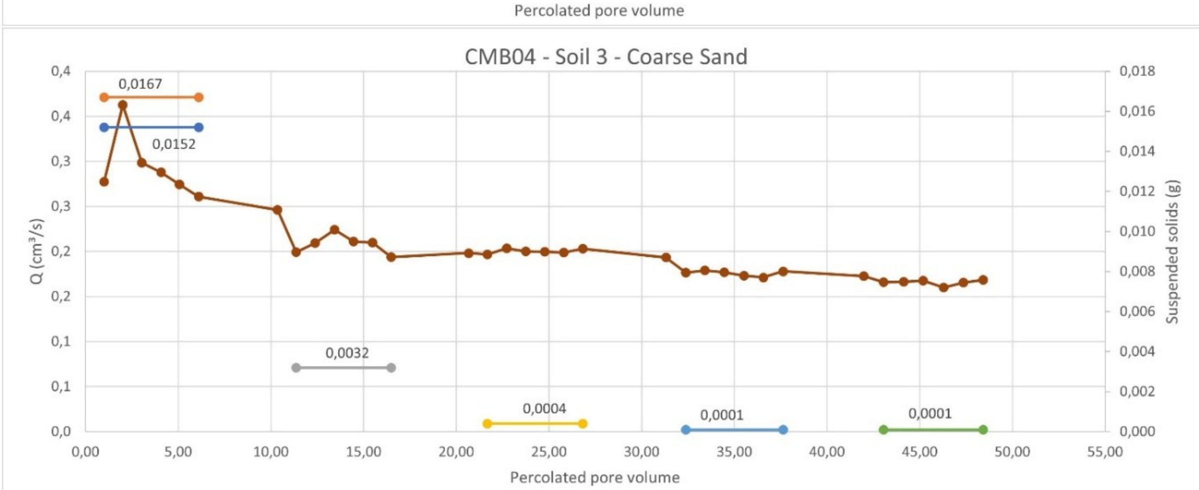

MB10 - Soil 3 - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,003
0,0017
0,0019
0,0045
0,0027
0,2
0,1
0,0
0,005
0,004
0,003
0,002
0,001
0,000
0,00
5,00
10,00
15,00
20,00
25,00
30,00
35,00
40,00
45,00
50,00
55,00

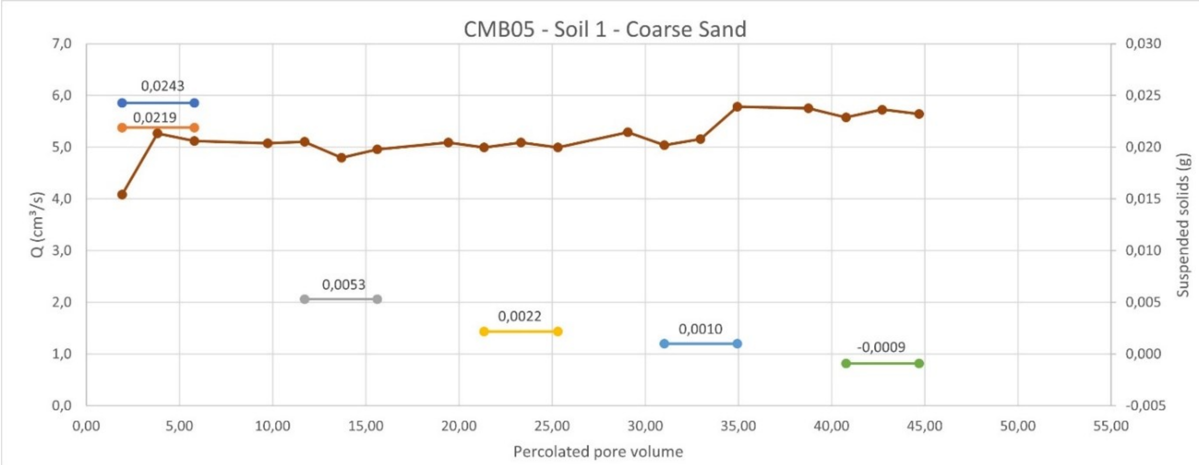

MB11 - Soil 3 - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0026
0,0006
0,0011
0,0003
0,0004
0,3
0,2
0,1
0,0
0,003
0,002
0,001
0,000
0,00
5,00
10,00
15,00
20,00
25,00
30,00
35,00
40,00
45,00
50,00
55,00

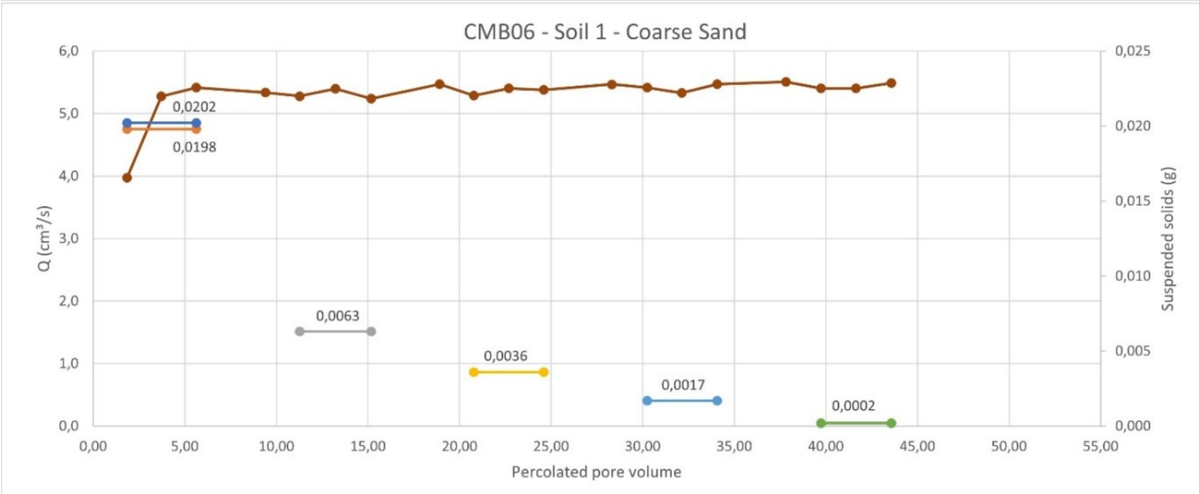

MB12 - Soil 3 - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0195
0,003
0,0006
0,0021
-0,0004
0,5
0,4
0,3
0,2
0,1
0,0
0,025
0,020
0,015
0,010
0,005
0,000
-0,005
0,00
5,00
10,00
15,00
20,00
25,00
30,00
35,00
40,00
45,00
50,00
55,00

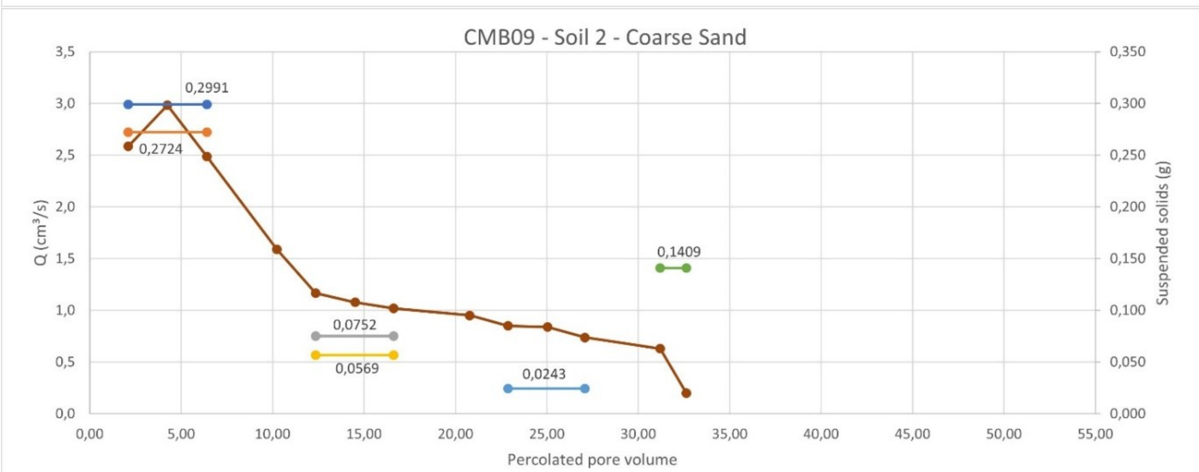

MB13 - Tailings - Natural Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0101
0,0007
0,0016
0,0001
-0,0021

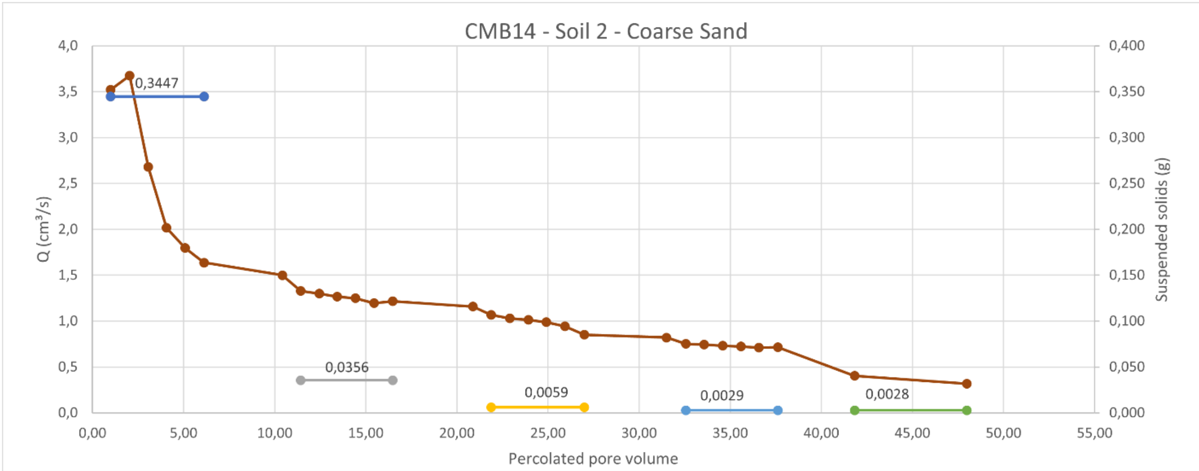

CMB02 - Soil 3 - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0194
0,0116
0,0044
-0,0001
-0,0009
0,0007

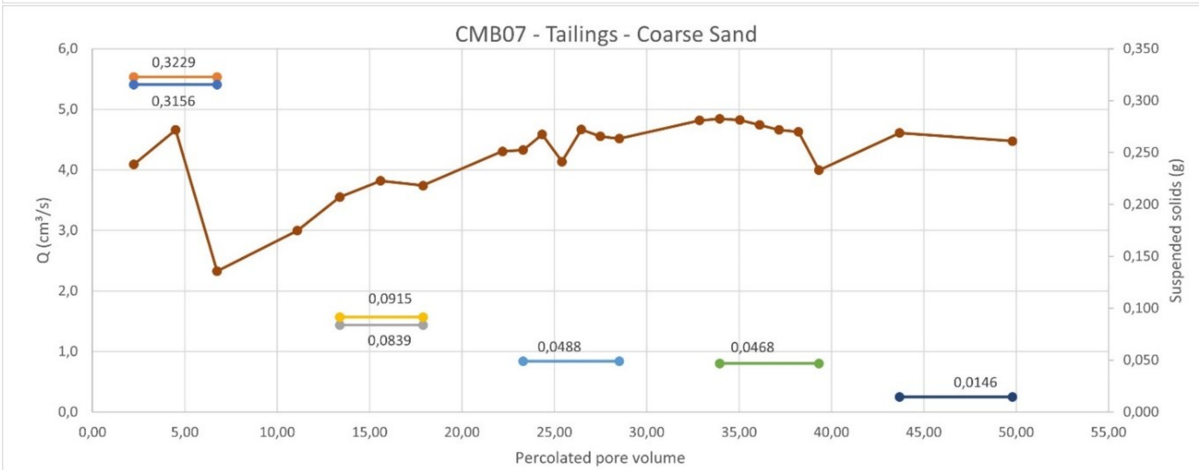

CMB04 - Soil 3 - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0167
0,0152
0,0032
0,0004
0,0001
0,0001

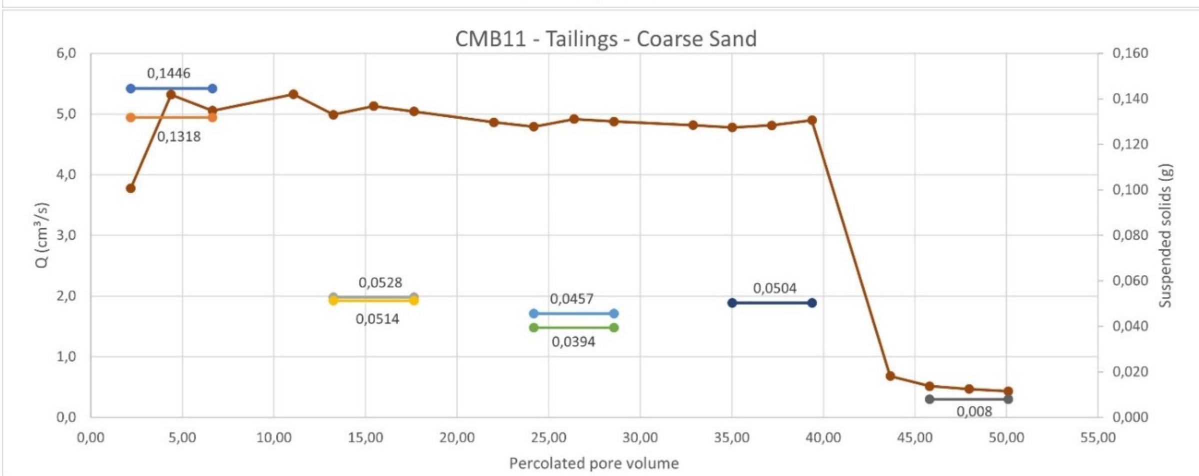

CMB05 - Soil 1 - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0243
0,0219
0,0053
0,0022
0,0010
-0,0009


CMB06 - Soil 1 - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,0202
0,0198
0,0063
0,0036
0,0017
0,0002


CMB09 - Soil 2 - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,2991
0,2724
0,1409
0,0752
0,0569
0,0243


CMB14 - Soil 2 - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,3447
0,0356
0,0059
0,0029
0,0028


CMB07 - Tailings - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,3229
0,3156
0,0915
0,0839
0,0488
0,0468
0,0146


CMB11 - Tailings - Coarse Sand
Q (cm³/s)
Suspended solids (g)
Percolated pore volume
0,1446
0,1318
0,0528
0,0514
0,0457
0,0394
0,0504
0,008