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Long-term analysis of clogging and oil bio-degradation in a System of Catchment, Pre-treatment and Treatment (SCPT)

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ABSTRACT

Runoff contamination has motivated the development of different systems for its treatment in order to decrease the pollutant load that is discharged into natural water bodies. In the long term, these systems may undergo operational problems. This paper presents the results obtained in a laboratory study with a 1:1 scale prototype of a System of Catchment, Pre-treatment and Treatment (SCPT) of runoff waters. The analysis aims to establish the operational behaviour of the SCPT in the long term with respect to oil degradation and hydraulic conductivity in the geotextile filter. It is concluded that bio-degradation processes take place inside the SCPT and that hydraulic conductivity of the geotextile filtration system decreases slowly with successive simulated runoff events.

1. Introduction

It has been widely demonstrated that runoff drags with it a large amount of pollutants present on impervious urban surfaces [1–4]. There are devices especially designed to minimize the runoff pollution and they are included in the category of Best Management Practices (BMPs). Nevertheless, most of these devices do not perform satisfactorily, providing low reliability in their treatment efficiency [5]. In fact, under certain conditions some systems even have negative efficiencies [6–9].

In this context, the Construction Technology Research Group (GITECO), of the University of Cantabria, has developed a System of Catchment, Pre-Treatment and Treatment (SCPT) of runoff waters. This system aims to reduce the contamination caused by solids and oils in runoff waters originating from impervious pavements, mainly car parks. The background of this research was compounded mainly by previous studies about permeable pavements developed in the University of Cantabria [10,11] and the objective was to concentrate the benefits of a pervious area in one point, like a manhole.

The solids and oil treatment efficiencies of the SCPT are higher than 80% [12]. This paper analyzes the capacity of the SCPT elements to provide an environment to shelter colonies of microorganisms specialized in biodegrading retained oils. In addition, the possible causes of the decrease in hydraulic conductivity are studied.

2. Materials and methods

2.1. Prototype description

The research was carried out in a laboratory prototype (scale 1:1) of the System of Catchment, Pre-treatment and Treatment (SCPT) of stormwater runoff, described by Castro-Fresno et al. [13]. Fig. 1 shows the parts of the SCPT and their complementary elements.

The SCPT prototype consists of a methacrylate structure of 0.80 m width, 1.30 m length and 1.0 m height. Its inner space has a screen installed at 0.25 m from the bottom, which divides it into two parts. The first part of the SCPT prototype is where the runoff enters and where a hydraulic plug is placed to retain oils. The second part contains a decantation volume and a filter system, before the outlet.

The decantation volume is 1.10 m long, 0.80 m wide and 0.45 m high. The filter system is placed over the decantation volume. For this research, the filter system is made of Polyfelt TS30® geotextile

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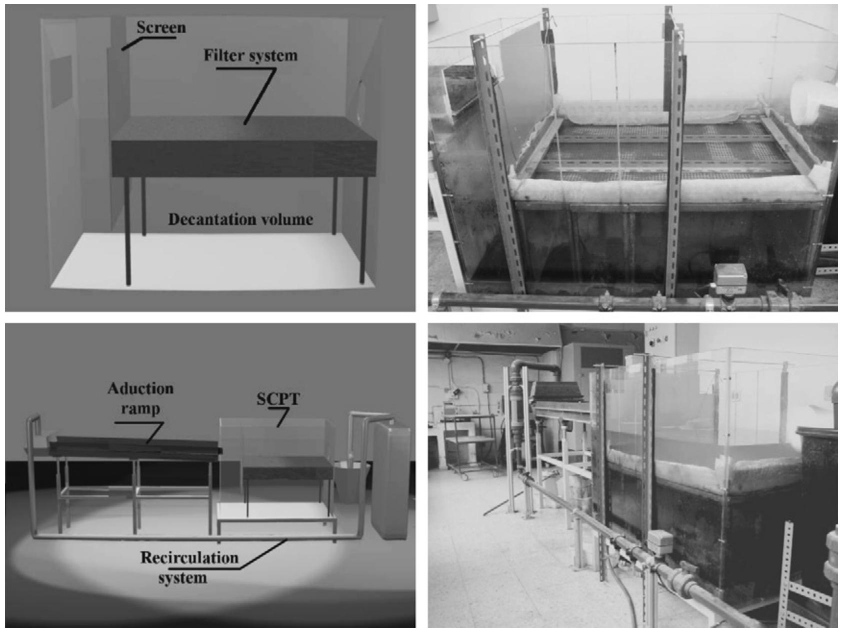

Fig. 1. SCPT configuration used in this research.

(two layers), PVC nets and a metallic frame. These last two elements are used to strengthen the system. The filter system is 0.80 m wide and 1.10 m long. Four metallic bars of 2.5 kg each are added as extra weight, one on each side of the rectangular metallic frame.

An adduction ramp and a recirculation water system are used, as complementary elements specifically designed for runoff simulation. The impervious surface is simulated in the adduction ramp by a layer of slurry; this layer emulates the superficial characteristics of an impervious asphalt pavement. The recirculation system has a 1.0 m^3 accumulation tank, two pumps, one flow meter and one extra filter. The pumps conduct the water through pipes from the accumulation tank to the top of the adduction ramp and, once the water has left the SCPT, they return it to the accumulation tank. A filter is placed in this last part to remove the pollutants that still remain in the water after passing through the SCPT.

2.2. Test description.

2.2.1. Hydraulic conductivity of different geotextile types

The hydraulic capacities of three specific types of geotextiles were analyzed:

- Amopave®: polypropylene needle punched nonwoven geotextile with 100 mm of opening size and 90 mm/s of water permeability.
- Inbitex®: polypropylene and polyethylene thermally bounded nonwoven geotextile with 100 mm of opening size and 100 mm/s of water permeability.
- Polyfelt® TS 30: polypropylene needle punched nonwoven geotextile with 145 mm of opening size and 80 mm/s of water permeability.

These geotextiles were chosen for their proven capacity to provide a suitable environment for a Hydrocarbon Degrading Bacteria (HDB) film [11].

In the test, five double samples of each geotextile were used; to represent the 2 layers in the SCPT filter system. The samples were 55-mm diameter discs. The samples were tested with perpendicular flow analysis equipment in the Geosynthetics Laboratory of the University of Cantabria (LAGUC).

The test is based on UNE-EN ISO 11058:1999, with the procedure adapted to the specific requirements of this research. Each test sample was tested five times; with 1 day between tests.

The complete test procedure consists in:

1. Placing the test sample on the test equipment.
2. Starting the perpendicular water flow.
3. Waiting till the difference of water level before and after the test sample is 70 mm.
4. Maintaining the difference of 70 mm until the flow is stable.
5. Taking note of the stabilised flow.

2.2.2. Hydraulic conductivity in the SCPT

Since the re-suspension of retained pollutants is one of the problems of this kind of BMPs [14], the test objective is to determine the SCPT behaviour when faced with successive runoff events that drag solids and oils. Between the consecutive events the pollutants retained inside the SCPT are not removed in order to cause their re-suspension during the following events.

The solids used in this research were fitted to the size distribution described by Zafra Mejía and Temprano González [15], for the north of Spain (Fig. 2). The oils correspond to used

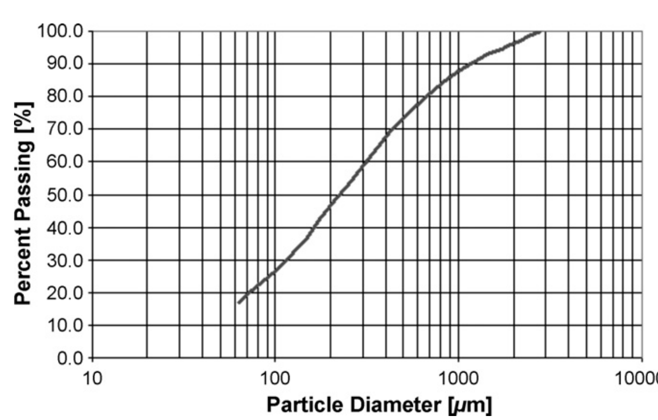

Fig. 2. Distribution of the solid size used in this research (Zafra Mejía and Temprano González, 2005).

Fig. 3. Water level difference between the zone of the hydraulic plug and the zone over the filter system of the SCPT.

engine oil, following the criteria established in previous research [11,16,17].

The inflow is equivalent to the runoff generated in a car park of 8 places with its access road in Santander (north of Spain), under a rain with a 2-year return period and a 10-min concentration time. Applying the rational method, a 1.7 l/s flow is calculated.

The test procedure is defined as:

1. Leak the pollutant onto the adduction ramp (solid and oil).
2. Runoff simulation for 20 min, by the recirculation system.
3. 10 min without flow to allow solid decantation.
4. Empty the SCPT, leaving 8 cm of water, to simulate the worst operation condition, especially in the case of solids.

For the duration of the runoff simulation, the water surface level difference was determined, between the hydraulic plug zone and the zone over the filter system, by photographic analysis (Fig. 3).

Two series of tests were carried out with the purpose of analyzing the possible effect of the solid and oil concentration on the water surface level difference on either side of the screen. The first, denominated high load, with 200 mg/l of solids and 20 mg/l of oil, and the second, denominated medium load, with 100 mg/l of solids and 10 mg/l of oil.

2.2.3. Oil bio-degradation test

The aim of this test is to prove the existence of oil bio-degradation microorganisms in the geotextile used as part of the filter systems in the SCPT. The sample extraction from the geotextile was carried out by scraping and cutting fibres of the geotextile with a sterilized scalpel. The Sample Extraction Zones (SEZ) were determined by a method of random sampling [18].

The procedure for choosing the SEZ consisted in dividing the geotextile area into cells of 10 cm by 10 cm. A frame of 10 cm width was eliminated, with the purpose of minimizing the influence of possible edge effects on the characterization of the filter system. Using this procedure the geotextile study area was divided into 54 cells, of which 14 were chosen at random to make up the set of the SEZ.

Each SEZ was divided into 8 cells, extracting a sample just once from each one of them. In order to avoid any bias in the sampling process, the order of the extraction of cells was also random.

Once the geotextile samples were extracted, they were processed with the aim of determining whether colonies of microorganisms were present. The procedure adopted consists in two parts:

- Extraction of the bacteria samples from the geotextile SEZ.
- Isolation and determination of the population of Hydrocarbon Degrading Bacteria (HDB) in the bacteria samples.

The extraction procedure consists in watering the geotextile sample in sterilized distilled water, in a proportion of 1:10 or 1:100, in relation to the amount of extracted geotextile sample. Then, the diluted sample is shaken in a vortex for 1 min, allowing a settling time for precipitation of solid particles [19–21].

From the floating content of the diluted sample, liquid samples with bacteria are extracted, which are used in the procedures of isolation and determination of the HDB population. 2 mg of sterilized used engine oil was added to the bacteria cultures, as a single source of carbon and energy. Then a Most Probable Number (MPN) analysis was carried out.

Table 1
Flow values for the geotextiles studied.

Geotextile	Event	Samples final flow (l/min)				
		1	2	3	4	5
Amopave®	E1	2.18	3.12	1.97	3.40	3.43
	E2	2.31	1.62	3.39	2.64	3.15
	E3	3.76	4.08	4.10	3.09	4.08
	E4	3.85	2.30	1.15	2.78	2.64
	E5	2.75	3.44	1.46	3.15	1.50
Invitex®	E1	2.35	1.66	4.08	2.55	1.23
	E2	1.86	1.14	1.99	1.49	3.62
	E3	2.21	1.40	2.22	2.21	3.38
	E4	3.59	1.55	3.12	3.30	1.70
	E5	3.53	1.98	2.14	2.46	1.89
Polyfelt® TS 30	E1	4.10	4.07	3.10	4.10	3.88
	E2	4.00	3.59	1.33	2.40	2.98
	E3	4.08	4.08	4.10	4.08	3.09
	E4	4.10	4.08	2.98	3.86	3.06
	E5	3.30	3.65	3.78	3.70	2.51

3. Results and discussion

3.1. Hydraulic conductivity in different geotextiles

The flow values for each geotextile studied are shown in Table 1. The Polyfelt® TS 30 is found to have the greatest flow over time, with values above 2.0 l/min (with the exception of one point only), reaching above 4.0 l/min in several cases. The lowest final flow values correspond to the Inbitex® geotextile, with a large number of values below 2.5 l/min. In the case of Amopave®, the final flow values are distributed homogeneously along the range from 1.0 to 4.0 l/min, without any predominant value.

Arranging the geotextiles in ascending sequence according to their final hydraulic conductivity, the sequence is: Inbitex®, Amopave® and Polyfelt® TS 30.

The Kolmogorov–Smirnov test concludes that the final flows have normal distribution (p-value 0.444). An ANOVA was carried out to determine if the flow value changes depending on the number of rain events or the geotextile type.

No difference was found in relation to the number of events. However, a difference was found concerning the type of geotextile (p-value < 0.05). Tukey's test concludes that Polyfelt® TS 30 has different final flow from the other two geotextiles, having the greatest final flow and, therefore, a greater hydraulic conductivity.

The presence of retained air in the samples and its influence on final flow values were also analyzed. The method used was visual analysis of the bubbles during the test. A T-test determined a sig-

Table 2
Values of the water level difference between the zones of hydraulic plug and the zone over the SCPT filter system depending on operation conditions and pollutant load.

Event	High load		Medium load	
	Clean SCPT	Unclean SCPT	Clean SCPT	Unclean SCPT
01		2.1	2.9	1.3
02		2.9	2.8	2.7
03	1.6	6.0	2.7	4.6
04	3.0	8.0	3.0	4.9
05	2.5	9.0	3.3	5.3
06	2.5	9.0	3.7	4.7
07	3.6		4.9	6.0
08			5.5	
09	5.2		5.4	
10	7.5		8.9	
11	6.3		7.5	
12			9.0	
13			9.1	

nificant difference in the values due to this factor (p-value < 0.05). Next, it was analyzed whether this difference occurred in all the geotextiles studied. It was determined that the difference exits in the case of the Inbitex® and Polyfelt® TS 30, but not in the case of the Amopave®. In all the cases, it was clear that the final flow is greater when there is no retained air in the geotextiles. Thus, it was concluded that the air presence in the geotextiles diminishes the hydraulic conductivity of the geotextile, but the number of events do not.

3.2. Hydraulic conductivity in the SCPT

The test series was focused on two pollutant loads: high and medium. For both scenarios, the initial condition is a clean, newly installed SCPT. Several runoff events were simulated till the filter was clogged. In addition, it was observed that the hydraulic conductivity loss is accumulative over time and, in the case under study, this loss reaches a maximum when the filter system is clogged. Then the geotextile was replaced but without cleaning the SCPT. The water level difference between the zone of the hydraulic plug and the zone over the SCPT filter system was determined before and after the change of the filter system. The values of the difference in the water level, operation conditions and pollutant load are shown in Table 2.

3.2.1. Clean with high pollution load

There are several curves that fit the data points with statistical significance with a 95% confidence level and with a coefficient of determination higher than 0.870. Applying the standardized coefficient of determination criteria, there are still several possible curves which fit. Finally, applying Occam's razor [22], the linear equation was chosen, because it is the simplest equation of all (Eq. (1)). Its graphical representation is shown in Fig. 4.

$$H_1 = 0.625n - 0.333 \quad (1)$$

where H_1: water level difference on the two sides of the SCPT screen, before filter system replacement (mm). n: Consecutive event number.

After replacing the geotextile in the filter system, there are several curves which fit for the values of the water level difference. All of them have a regression coefficient greater than 0.90, with statistical significance over 95%. The regression coefficients were used as a discriminating element, concluding that the cubic curve is the best one (Eq. (2)).

$$H_2 = 2.400 - 1.639n + 1.354n^2 - 0.150n^3 \quad (2)$$

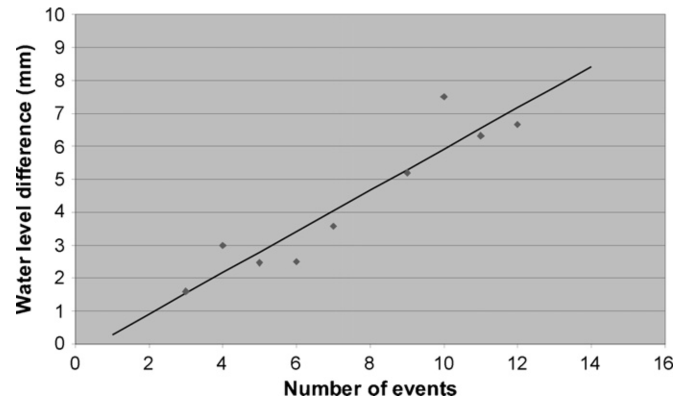

Fig. 4. Water level difference values and fitting curve for high load condition.

where H_2: water level difference between the two sides of the SCPT screen, after filter system replacement (mm); n: consecutive event number.

Comparing the rate of change H_1 (Eq. (1)) with H_2 (Eq. (2)), it can be observed that H_2 is clearly greater (Fig. 5). This implies that the hydraulic conductivity resistance of the geotextiles increases faster when the geotextiles of the filter system have been changed and the SCPT has not been cleaned. This is due to the re-suspension of the pollutants during the second stage.

3.2.2. Clean with medium pollution load

Using the values of the difference of the water levels with the initially clean SCPT, the curve fitting analysis produced several possible curves with a confidence level of 95% and with a regression coefficient higher than 0.900. With the standardized regression coefficient analysis, it was concluded that the cubic curve has the best standardized R^2, which was 0.934. Eq. (3) describes the curve fitting model that is shown in Fig. 6.

$$H_3 = 4.082 - 1.189n + 0.258n^2 - 0.011n^3 \quad (3)$$

where H_3: water level differences between the two sides of the SCPT screen under medium load conditions, before filter system replacement (mm). n: Consecutive event number.

After applying the standardized regression coefficient criteria, the best fit to the curve of the water level differences (once the filter system was changed) is the quadratic curve. This curve has the best standardized R^2, which is 0.866, and a confidence level higher than 95%. Eq. (4) and Fig. 7 describe that curve.

$$H_4 = -56.633 + 6.157n - 0.152n^2 \quad (4)$$

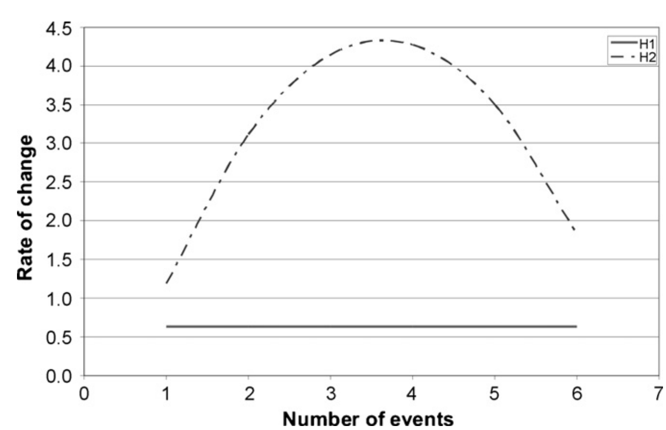

Fig. 5. Rate of change of H_1 and H_2.

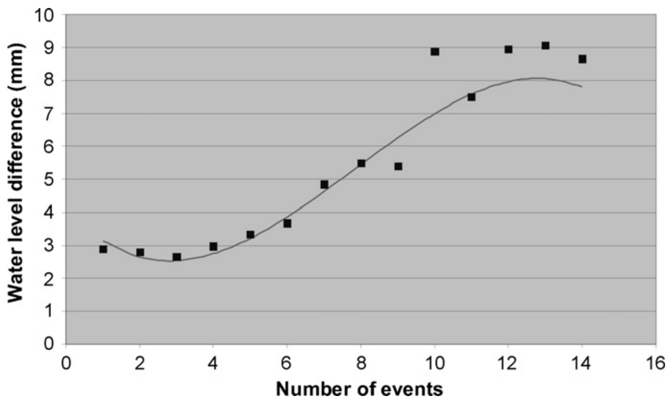

Fig. 6. Water level difference values and fitted curve for medium load conditions.

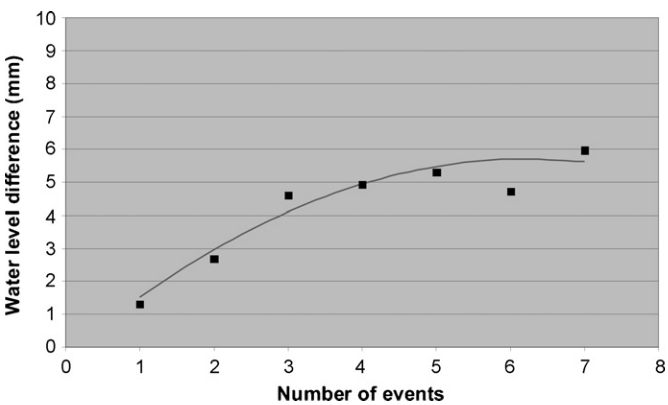

Fig. 7. Water level difference values and fitted curve for medium load conditions, after replacing the filter system.

where H_4: water level difference between the two sides of the SCPT screen under medium load conditions, after filter system replacement (mm); n: consecutive event number.

A comparative analysis of the rate of change of H_3 and H_4 revealed that H_4 has a greater value than H_3 (Fig. 8).

3.2.3. *Comparison of water level difference between high and medium load conditions before changing the filter*

The Kolmogorov–Smirnov test was applied to the set of data of water level difference values between the two sides of the SCPT Screen, under conditions of high and medium load. The results showed no normality of grouped samples (p-value 0.034). However, by a cube root transformation of the data, the normality of the grouped sample was obtained (p-value 0.194).

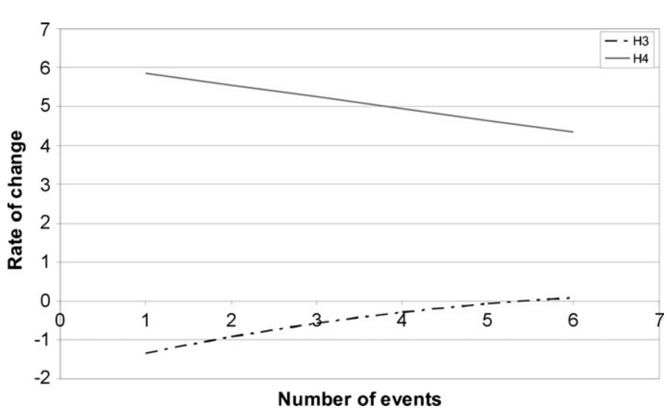

Fig. 8. Rate of change of H_3 and H_4.

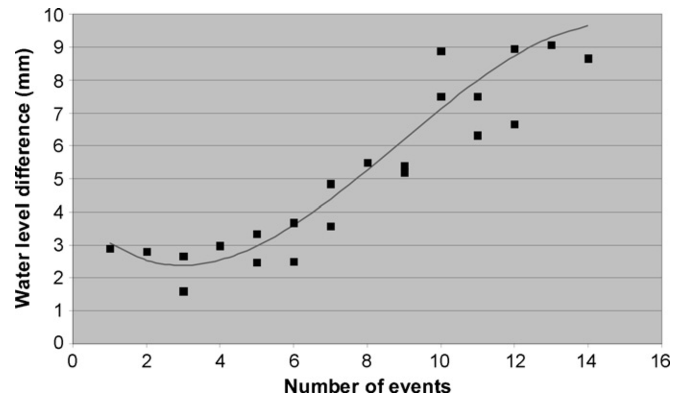

Fig. 9. Fitted curve for the water level difference values depending on the number of consecutive events.

Once the normality of the values was obtained, a T-test was carried out (p-value 0.25 [23]), concluding that the values of water level difference do not have a statistically significant difference between high and medium pollutant load conditions, with 95% confidence.

Considering all the data, the curve fitting analysis on the water level difference showed the cubic curve to be the best fit (standardized R^2 0.876). Eq. (5) and Fig. 9 represent the model adopted.

$$H = 4.012 - 1.179n + 0.239n^2 - 0.0009n^3 \quad (5)$$

where H: water level difference between the two sides of the SCPT screen. n: Consecutive event number.

This means that before changing the filter, the clogging process does not depend on the pollutant load. This is probably due to the air occluded in the geotextile voids, whose influence has previously been proved. It should be highlighted that during the test process, the air that is initially underneath the filter system is forced to go up through the filter system by the water ascending into the SCPT.

3.3. *Oil bio-degradation.*

The MPN values obtained for each section throughout the research are shown in Table 3. The first samples were taken 2 weeks after starting the test and the last one after 8 weeks. The population of HDB growth after 56 days was superior to the maximum of the scale, consequently this value was not considered in the statistical analysis of the results.

The measurement error due to this type of weekly sampling is less than 5% [18], a value that is considered acceptable for this research.

The Kolmogorov–Smirnov test applied to the average values of weekly MPN values leads to a p-value less than 0.05, so average values are not normal. However, carrying out a natural logarithmic transformation (Ln), the Kolmogorov–Smirnov test showed the normality of the transformed values with a p-value of 0.444.

These transformed values of the MPN fit with Eq. (6), verifying the assumptions about the residues using the Kolmogorov–Smirnov test (p-value = 0.168) and the Durbin–Watson value, which is 2.563.

$$\text{Ln(MPN)} = 8.875 + 6.922n \quad (6)$$

where Ln(MPN): natural logarithm of MPN. n: Week number.

Transforming the data to the primitive form, Eq. (7) is obtained.

$$\text{MPN} = 7150 * e^{6.922n} \quad (7)$$

Thus, it is found that the initial population is of 7150 and the intrinsic growth rate is 6.922

Table 3
MPN values for each week.

SEZ	Week					
	2	3	4	5	6	7
1	3.90E+10	8.44E+11	3.46E+11	4.65E+13	1.02E+15	1.62E+12
2	2.45E+11	1.35E+12	8.43E+10	3.90E+12	1.20E+16	2.67E+11
3	2.45E+09	3.90E+10	1.06E+11	8.47E+12	1.56E+13	1.32E+17
4	2.45E+11	3.91E+09	3.69E12	5.87E+13	1.32E+15	3.06E+21
5	1.64E+10	1.63E+11	4.76E+15	1.87E+14	1.87E+13	1.93E+25
6	6.37E+09	8.61E+09	4.98E+15	3.83E+13	2.14E+19	1.35E+26
7	2.44E+10	1.32E+11	9.67E+15	3.90E+12	4.60E+13	1.35E+26
8	6.37E+10	6.82E+12	1.63E+11	1.32E+14	8.43E+15	1.20E+27
9	2.44E+10	1.06E+11	2.24E+16	2.26E+13	5.87E+22	1.20E+27
10	3.91E+09	8.44E+09	5.37E+13	2.44E+12	6.50E+24	1.58E+25
11	3.91E+11	1.98E+10	2.54E+15	3.42E+13	2.24E+18	7.80E+22
12	2.47E+10	2.26E+09	4.59E+17	8.43E+13	2.49E+13	1.68E+24
13	8.47E+12	1.08E+10	6.19E+16	9.67E+14	2.23E+15	2.34E+17
14	3.90E+10	8.47E+10	5.35E+13	1.01E+13	1.80E+14	1.32E+25
Media	6.85E+11	6.85E+11	4.04E+16	1.14E+14	4.68E+23	1.94E+26
% Error[a]	1.8	2.0	3.3	1.2	3.5	4.7

[a] % Error: the percentage error in the measurement with respect to the average value.

These results confirm that in the geotextile layer of the SCPT a bio-film is created, whose growth is exponential. This type of growth is characteristic of microbial populations without growth limitations. That means that the SCPT filter system has the necessary carbon sources for the development of the bio-film.

Considering that these colonies had the used engine oil as the only source of carbon and energy, it can be concluded that these colonies are formed by microorganisms specialized in hydrocarbon degradation (HDB).

About the source of oxygen when there is a water layer over the filter system, retention of air bubbles in the geotextiles could be beneficial for the microorganism colonies, since these bubbles are a reservoir of oxygen for these periods.

4. Conclusions

The hydraulic conductivity of the filter system, made of geotextile material, does not undergo significant variations in its behaviour due to the different solid and oil loads used during the test with the SCPT. The hydraulic conductivity loss seems to be more related to the presence of air bubbles in the geotextiles.

The decrease of the geotextiles' hydraulic conductivity is higher when a new filtering system is installed and the pollutants inside the SCPT are not removed. This is a clear indication of the negative effect on the hydraulic conductivity of pollutant re-suspension and retention of air bubbles.

This research determined that the geotextiles of the SCPT filter system are colonized by hydrocarbon-degrading microorganisms. The growth of these colonies for the monitored period of eight weeks is exponential under conditions of addition of oil.

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