# Temporal analysis of side effects produced by foam agents in the soil excavated with Earth Pressure Balance (EPB)

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**Abstract.** The use of foaming agents, is a tunneling technique frequently used with Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). The main objective of the Materials and Processes for Sustainable Construction (MaPCoD) project is to characterize the treated material with foaming agent, during its evolution over time. Indeed there are few studies presenting a research methodology to evaluate the degradation of pollutant in soils, like the foaming agent used. The foaming agents are surfactant-lubricant chemical compounds. The air system of TBM and foaming agents create bubbles, which are integrated with the soil, this treatment changes the hydro-mechanical properties, allowing easy excavation. Degradation tests (spirometry), viscosity tests (capillary viscometer), mechanical tests (compressibility, consolidation, shear tests and triaxial tests), and curves of water retention over time were used to describe the soil's behavior. The hydro-mechanical properties are not drastically changed after the treated soil reaches 50% of degradation.

**Keywords.** Degradation, Earth Pressure Balance (EPB), Foaming agents, Retention curves, Sandy clay soil, Tunnel Boring Machine (TBM)

## 1. Introduction

Two types of earth pressure machines are frequently used for urban soils: Earth Pressure Balance (EPB) and Slurry shield machines. Slurry shield machines are used for works with large-sized soils, while EPB are used for works with fine soils.[1, 9, 10.]

The EPB Tunnel Boring Machine (TBM) uses surfactant agents in order to condition soils during digging. The first injection of foam is executed on the EPB shield and a second into the bulk chamber over extraction. This process is done in order to change the hydro-mechanical properties of the soil and aims to facilitate the excavation.[6]

Micro-bubbles generated by the surfactant separate the solid grains in the soil. This separation has the following effects: a decrease in surface tension and an increase of fluidity and electrostatic repulsion between grains.[7, 11]

Previous works expose the effects on the hydro-mechanical properties because of the soil treatment by surfactant, but they did not study the evolution of the treated soil properties due to the degradation of the foam generated by the surfactant. [4, 5]

The purpose of this work is to analyze the effect of the surfactant and the changes the hydro-mechanical properties of the treated soils undergo over time from a series of experimental tests.

## 2. Materials and methods

### *2.1. Studied soil*

In this study, a sandy-clay soil was used and was adapted to an EPB shield and to the use of surfactant. It is classified as an A1 soil following the French GTR classification (NF P 11-300). Table 1 provides some physical characteristics of the soil.

**Table 1. Initial properties of the studied soil**

| | |
|---|---|
| Initial water content fixed (%) | 22 |
| The proctor optimal water content w (%) | 12% |
| Liquid limit wl(%) | 22,9 |
| Plastic limit wp(%) | 15,4 |
| Liquidity index Ip (%) | 7,5 |
| VBS | 1,75 |
| Unit weight of solid particles γs (kN/m$^3$) | 26,36 |

### *2.2. Foam agent*

The foaming agent used was CLB F5™ from CONDAT. The CLB F5™ makes soil extraction safer and more efficient under the severe jobsites conditions.

The dosage of this surfactant in the soil is defined using the following four parameters. Surfactant concentration (Cf [%]), defined as the concentration of the additive in the foam; Foam Expansion Ratio (FER [%]) which is the ratio between the volumes of liquid surfactant and the foam produced; Foam Injection Ratio (FIR [%]): which indicates the volume of foam used per volume unit of excavated soil and Liquid injection Ratio (LIR [%]) which is the ratio between the FIR and the FER.[5]

Several mini-slump tests were conducted to find the optimal dosage. The optimal values parameters obtained for the tested A1 soil are $C_f$ =3%; FER=10%; FIR=150% and LIR=15.

### *2.3. Experimental tests*

The CLB F5™ is defined as quickly degradable, according to degradability tests carried out by the laboratory CONDAT. 60% of the product is degraded in 7 days, and at 28 days, 90% of the degradation is achieved. The foam’s degradation curve cannot be submitted by request of the producer.

The hydro-mechanical characteristics of the soil after the foaming agent injection were monitored. In a first part, a soil degradation test was performed using the spirometer method. This test gives an idea of the degradation rate of the foam in the soil, which allows to plan later the treated soil's characterization tests. It was decided to do daily tests for the first week due to the high levels of degradation speed.

In a second part, the results of the permeability, the oedometer and the shear stress tests for the treated samples are compared with the results of the untreated soil.

Finally, triaxial tests were conducted in order to define the permanent changes of the soil's hydraulic properties. (figure 1)

The developed methodology for the experiment is presented in figure 1.

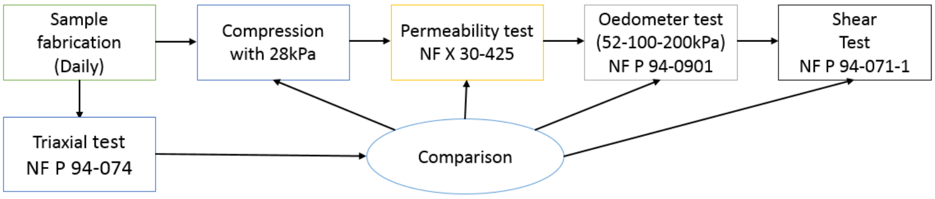


Figure 1. Methodology for the experimental campaign

## 3. Results and discussion

### *3.1. Degradation tests*

Three complementary spirometer tests were executed (Figure 2). These tests were performed according to standard NF EN ISO 9408.

The results show that, in all three conditions (200 g of untreated soil, 200 g of soil + foam and 100 g of soil + foam + 100 g of referenced soil containing bacteria) two degradation speeds were obtained. It was found that these speeds differed in a turning point 5 days after injection of the foam. Accordingly, the greatest changes in the ground and its recovery due to the degradation of the foaming agent are manifested in this interval of time (0-5 days). So, it was decided to study the behavior of the samples each day during the first 7 days and later on the samples were checked every 3 days until the 28th day.

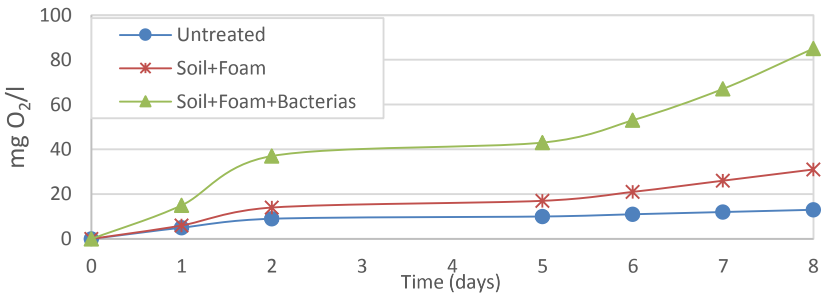


Figure 2. Degradation test results with spirometer (T.Vogel)

### *3.2. Capillarity test of the foam agent*

According to the specialized literature of the state of art of tunnels projects, the measurement of the viscosity of the additives by means of the capillary viscometer is recommended [10]. This test is carried out with an unleashed biological reaction. The kinematic viscosity is calculated from three measurement tests each day.

This test quantifies the viscosity that can affect the hydro-mechanical properties of the soil. The test done shows an average kinematic viscosity of $\mu$=1.08 $mm^2/s$ (during the 28 days the soil was tested). For the other hand, the kinematic viscosity of water for the untreated condition was 1.01 $mm^2/s$.

According to Houlsby, G et al. (2001), these results are explained by the presence of a viscous layer between the soil grains when the soil was mixed with the foam.

### *3.3. Hydro-mechanical tests*

The water content was constant in the samples during the 28 days period (w (%) was between 23.5%-21%). With this condition, the degradation effects in the soil were measured. The first affected property was the unit weight. The change was notable during the early 10 days, but after this period, the value returned to be the same as the one of the untreated condition. The change of the unit weight in the treated soil is due to the decrease of bubbles over time.

Table 2. Evolution of the unit weight over the time

| | Untreated | Treated Soil | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0 days | 1 day | 2 days | 3 days | 4 days | 5 days | 6-28 days |
| γh (kN/m3) | 20.4 | 18.4 | 19.0 | 19.1 | 19.8 | 19.9 | 20.1 | 20.2 |

#### *3.3.1. Permeability test*

A falling head permeability test was performed on an untreated soil sample consolidated under a stress state σ=28 kPa and the permeability value obtained was $K_w$= $3,32.10^{-9}$ m/s. Later, falling head permeability tests were performed on treated soil in the course of time. figure 3 shows a significant reduction in the permeability of the soil. Over time, permeability increases once again, but without reaching the initial value of the untreated soil.

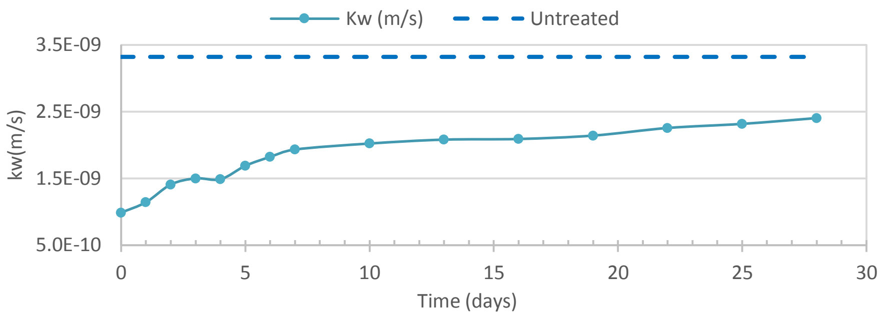


Figure 3. Evolution of the permeability over time

This phenomenon is expected due to two factors: the first is that there is an unsaturated condition during the early eight days, so the bubbles decrease the permeability in this interval of time. The second reason is derived from the viscous aspect of the foaming agent which prevents the flow of water in the soil.

*3.3.2. Evolution of the water retention curve*

The total suction value was measured on the equalized specimens by means of a dew-point chilled-mirror psychrometer (WP4C PotentiaMeter®).[3]

The curve corresponds to the normal behavior of a normal sandy-clay soil. In this case, the curve was modeled using the van Genuchten model equation:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{(1+(\alpha|\psi|)^n)^{1-\frac{1}{n}}} \quad (1)$$

Where

- θs and θr: saturated and residual water content, correspondingly [-]
- α and n: empirical parameters [$L^{-1}$], [-]
- $\psi$ : suction [L]

Figure 4 shows the water retention curve at different stages of degradation of the foaming agent in the soil. Firstly, it is noted that the condition of the soil leads to a change of the saturation water content. This change is directly linked with the change of void ratio over time and because of the integration of air bubbles in the soil.

The most important change found in this test was the decrease of the value of air entry suction $\psi_a = \frac{1}{\alpha}$, which at the 22nd day of injection was not the same as the value of the untreated soil. This parameter shows that when the water content is high (θ>35%), the treated soil can enter the unsaturated condition easily. This change is manifested with a decrease of permeability (figure 3).

However after 22 days, the $\psi_a$ suction value changed. The difference with the untreated value was 5.36 kPa, but this value is not significant.

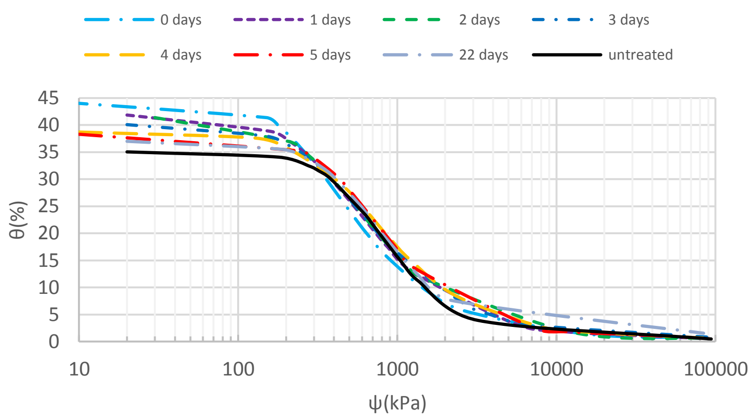


Figure 4. Evolution of the untreated soil water retention curve

*3.3.3. Oedometer tests*

An oedometer test was done on saturated soil. The strains used in this test were 27, 52, 101, 199 and 396 kPa. For the untreated soil, the results showed a compression index of $C_c$=0.113. The soil is therefore moderately compressible. The consolidation coefficient obtained was $C_v$=0.0320 $cm^2$/min and the initial void ratio of soil obtained was $e_i$=0.58.[12]

The samples were made each day for the treated soil. The evolution of the treated soil void ratio was analyzed. figure 5 shows a histogram of different states of consolidation (28-52-100-200 kPa). It is clear that the foam causes immediately high increase of the void ratio of the soil, but this value decreases over time; it tends to reach the same value of the untreated soil void ratio. From the 16$^{th}$ day, the void ratio was the same as the untreated ratio.

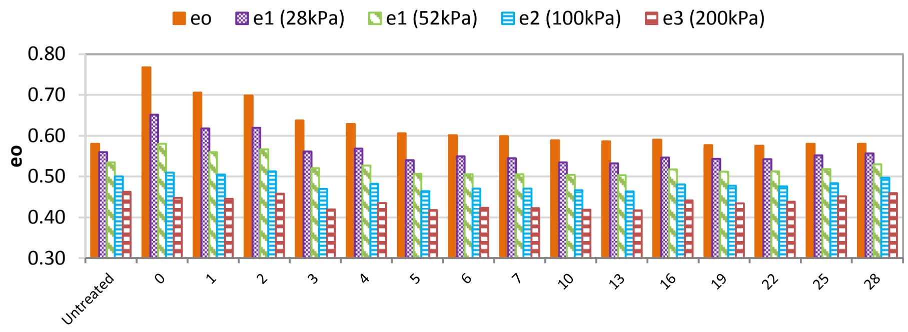


Figure 5. Evolution of the void ratio overtime

The oedometer modulus was calculated. This modulus undergoes resilience over time, therefore, the histogram (figure 6) presents the evolution of this parameter. The resistance is the same after the 16$^{th}$ day, when the degradation degree was 80%. With low pressures (52-100kPa), the change is more evident, during the early 8 days, where there is presence of bubbles. Accordingly, the resistance is directly linked with the degradation state.

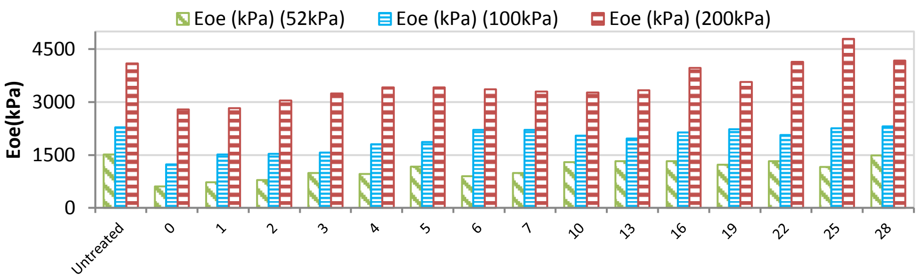


Figure 6. Evolution of the oedometer modulus

Figure 7, where the consolidation coefficient is plotted against time, shows clearly this result. The compression resistance is linked to the degradation state (Figure 2) and from the 16$^{th}$ day, the coefficient of consolidation was the same compared to the untreated condition.

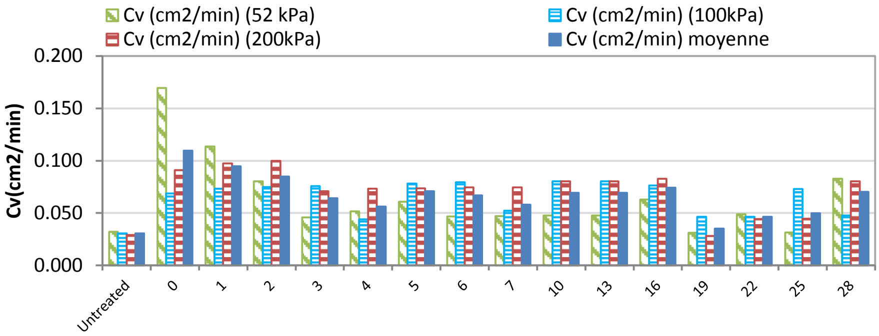


Figure 7.Evolution of the consolidation coefficient over the time

The temporal evolution of the compressibility factor $C_c$ is presented in Figure 8. The injection of foam transforms the soil in a viscous paste, consequently this material is more compressible. The result of the test confirms the physical degradation of the surfactant. Over time, the soil recovers its initial characteristics. The $C_c$ value during the early 8 days is the consequence of air bubbles, afterwards it is related to the degradation state. From the 22$^{th}$ day, the $C_c$ reached a similar value as the one of a soil without injection of foam.

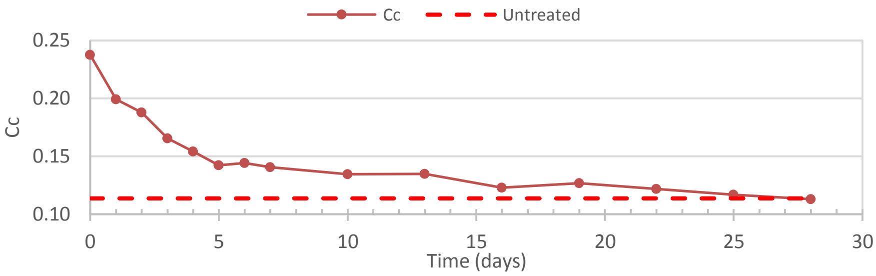


Figure 8. Evolution of the compressibility coefficient over time

### *3.2.4 Shear test*

Direct shear tests were carried out with consolidated and undrained conditions (UC) with three normal strains of 37, 148, and 287 kPa. A Mohr-Coulomb failure envelope criterion for each test was defined by linear least –square regression with a non-negative intercept. The angle of the envelope represent the friction angle and the intercept denotes the cohesion value. In the untreated samples, the cohesion value was $C_{cu}$=2.1 kPa and the internal friction angle $\Phi_{cu}$=23.2.

Tests with treated soil samples were carried out over time under the same conditions. Figure 9 shows the change of the angle of internal friction during the degradation of the foam. It can be observed that the soil recovered the friction properties on the 22$^{nd}$ day.

It was found moreover that the vertical displacement in the untreated soil is null, but the treated soil presents dilatancy due to the bubbles of the foam. Finally, the soil goes back to its initial behavior over time.

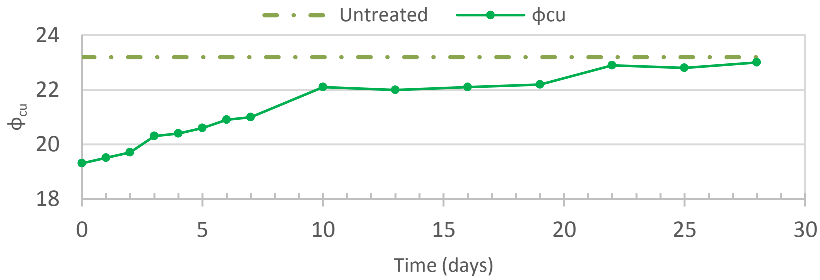


Figure 9. Evolution of the internal friction angle over the time

Also, it was observed that the recovery of the internal friction angle is proportional to the recovery of the void ratio (Figure 5). These results are similar to the results of the studies done by Houlsby, et al. (2000) and Bolton, M. D, (1986).

## 4. Triaxial test

The triaxial tests were also made under consolidated-undrained condition (CU). The samples tested were of untreated condition and of treated condition after 28 day. The advantages of the triaxial test are the possibility to control the level of saturation and the consolidation state.

The internal friction angle ($\Phi_{cu}$) did not show significant modifications in the triaxial test. It was found that the internal friction of the treated soil is not affected after 90% degree of degradation of the foam. However, the results of the direct shear test are higher. This increase is consequence of the better precision of the triaxial test.

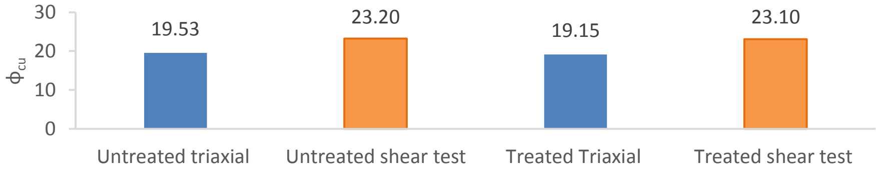


Figure 10. Change of the internal friction angle (28 days, Triaxial and shear tests)

In fact, cohesion was the parameter most affected in the triaxial test, although the untreated condition presented a low value of cohesion in the shear test (29.61kPa), it was reduced drastically to 1.07 kPa. In the shear test of the triaxial test, the cohesion was not very evident. This shows that the effect of separation of soil particles by the foaming agent has direct effects on the loss of soil cohesion.


Figure 11. Change of cohesion (28 days, Triaxial and shear tests)

Finally, the undrained tangent modulus was evaluated with stress-strain curves of the soils for different cell pressures. Apparently there were slight reductions either at low or high confining pressures. This was a permanent change, perhaps related to the loss of cohesion shown above.

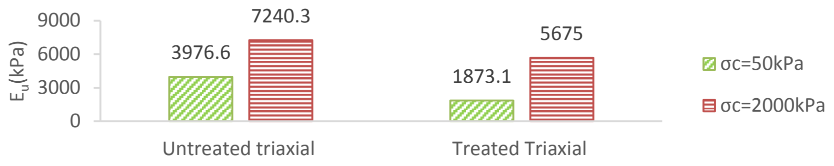


Figure 12. Change of the undrained modules (28 days, Triaxial and shear tests)

## 5. Conclusions

The foam agent is quickly degradable. This condition affects directly the evolution of the properties of the soil. Foams serve to reduce the permeability of the soil. This reduction was proven with the used water retention test, which shows reduction of air entry suction. It was also found, that the soil becomes more susceptible to have an unsaturated behavior. Although when the foam is used, the change doesn't have a relevant influence.

Tests on sandy-clay soil with injection of foam mixtures have demonstrated that there are remarkably high void ratios at stresses up to about 100 kPa. Compressibility and strength characteristics can play an important role in modifying a soil/foam mixture. The $C_c$ and $C_v$ increase on account of high voids but their initial values are recovered 22 days after the injection. High void ratios in the treated soil showed extremely low friction angles in the direct shear test. Nonetheless, this parameter recovered over the time. The triaxial test confirmed this recuperation. The cohesion was affected permanently because the foam agent has an anti-cohesive effect in the soil, but the values of cohesion generally were lower because the injection of the foam destroys any history of stress in the material.

Resistance is a factor affected permanently. In the oedometer test this change was not obvious, but the triaxial tests showed a slight reduction of 20% of the undrained modulus value.

In general, the expected impact of the foam agent on the environment was low if the substances are dosed adequately. The soil recovers its properties over time. This starts to give some indications of its potential practical use in different civil engineering projects.

## 6. Acknoledgment


The authors are thankful to CONDAT Lubrifiants, for providing the foaming agent CLB F5™ during the experimental campaign. Trust between our academic institutions and this company helped identify effects of their product and evaluate them in environmental terms.

The degradation tests were performed by T. Vogel from Environmental Microbial Genomics Group, Ampère laboratory, UMR CNRS 5005, Ecole Centrale de Lyon.

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