Effects of an Added Foaming Agent on Hydro-Mechanical Properties of Soil

Moez Selmi, Mariem Kacem, Mehrez Jamei, Philippe Dubujet

Abstract**—**Earth pressure balance (EPB) tunnel boring machines are designed for digging in different types of soil, especially clay soils. This operation requires the treatment of soil by lubricants to facilitate the procedure of excavation. A possible use of this soil is limited by the effect of treatment on the hydro-mechanical properties of the soil. This work aims to study the effect of a foaming agent on the hydro-mechanical properties of clay soil. The injection of the foam agent in the soil leads to create a soil matrix in which they are incorporated gas bubbles. The state of the foam in the soil is scalable thanks to the degradation of the gas bubbles in the soil.

Keywords**—**EPB, clay soils, foam agent, hydro-mechanical properties, degradation.

I. Introduction

TWO types of earth pressure machines are frequently used for urban soils: EPB and Slurry shield machines. Slurry shield machines are used for the works with large-sized soils, while EPB are used for the works with fine soils [1],[9].

The EPB Tunnel Boring Machine (TBM) uses surfactant agents in order to condition the 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], [2].

Previous works expose the effects on the hydro-mechanical properties of the soil treatment by surfactant in order to have a better excavation. But they did not study the behavior of soil excavated embankments after tunnel excavation [8], [11].

The purpose of this work is to analyze the changes of hydro-mechanical properties in the treated soil due to degradation of the foam from a series of experimental tests.

II. Materials and Methods

A. Studied Soil

In this study, a sandy-clay soil model is selected so that it is suitable for digging by EPB. This soil is composed of 60% Hostun sand and 40% clay (kaolinite). According to the French classification GTR (NF P 11 300), these soils correspond to A1. Fig. 1 shows the graduation curve of the model chosen soil.

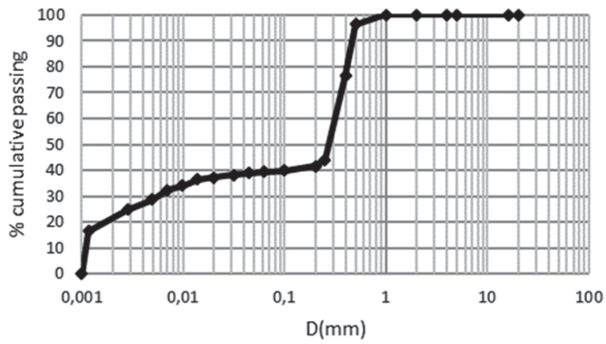

Fig. 1 Graduation curve of model soil

Physical characterization tests have been realized on the soil to identify their initial properties. These properties are summarized in Table I.

TABLE I
INITIAL PROPRIETIES OF THE STUDIED SOIL

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/m3)	26,36

B. Foam Agent

The foam consists of a gas bubbles dispersed in a liquid which contains a certain amount of surfactants. The bubbles are in the range of colloid size (1 to 1000 mm) [4]. The foaming agent used was CLB F5™ from CONDAT (company specializing in industrial lubricants). 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 by using the following three parameters [5], [3]:

- Foam Expansion Ratio: FER (%): $FER = \frac{Vdm}{Vm}$
- Foam Injection Ratio: FIR (%): $FIR = \frac{Vm}{Vsol}$
- Surfactant dosage: Cf (%): $Cf = \frac{m.at}{m.dm}$

where Vdm is the volume of the initial liquid solution, Vm is the foam volume, Vsol the soil volume, m.at the additive mass, and m.dm the mass of the surfactant solution.

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C. Experimental Tests

The hydro-mechanical characteristics of the soil after the foaming agent injection were analyzed. oedometric tests were performed with different percentages of FIR. It aims to study the effect of the foam injection ration FIR on the compressibility of the soil and describe the degradation of bubbles generated by the foam under effect of load.

Shear stress tests with different shear rates and different FIR are also performed on the treated soil.

Finally, permeability tests are conducted at different loading to study the effect of foam degradation on the permeability of treated soil.

III. Experimental Results

A. Foam Degradation

The foam produced by the surfactant is a dispersed gas bubbles in a liquid. The molecules of the surfactant provide protection of bubbles through a thin liquid film which surrounds them. Degradation and crushing of the foam bubbles is related to the drainage of liquid which surrounds the bubbles of gas. Fig. 2 shows the structure of the foam in the initial state and after 4 hours at atmospheric pressure.

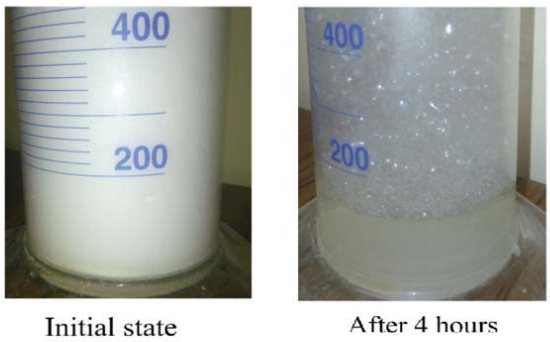

Fig. 2 Foam structure evolution

The degradation of these foams is connected essentially to the drainage of liquid that protects the gas bubbles under the effect of gravity. Then, analysis of the degradation of the foam is assigned to the flow rate of the liquid comprised in the foam.

The degradation of the foam test involves introducing a determined mass of the foam in a test tube and measure the volume of liquid leached over time. The half-life corresponds to the recovered mass of liquid which is equal to the half of the introduced foam [10], [8]. This test is performed on the foam formed from the CLB F5 agent provided with Cf = 3% and FER = 10% (Fig. 3). These results show that at atmospheric pressure the foam is rapidly degradable with a half-life equal to 19 minutes. This is thanks to the aging of the liquid film which surrounds the bubbles. The exchange of pressure between the atmospheric air and the bubbles leads to the expansion of bubbles during the aging.

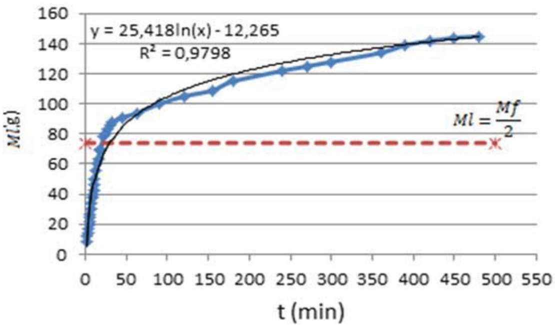

Fig. 3 Aging of the foam over time

In the soil, the process of degradation of the foam is different. This degradation is affected by several parameters. Indeed, the low permeability and low exchange of air with atmosphere in our soil will slow the drainage liquid processes, therefore the degradation of the foam. On the other side, the interactions between the gas bubbles and ground grain and loads applied to the soil will accelerate the crashing of bubbles. Fig. 4 shows the structure of soil-foam.

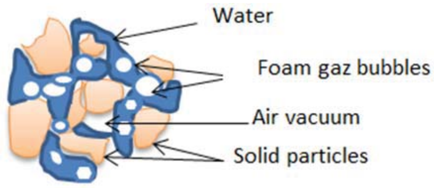

Fig. 4 Structure of soil-foam matrix

In the following parts, from experimental tests in various treatment conditions, we try to explain the effect and behavior of the foam in the soil model.

B. Oedometer Tests

In this part, we study the effect of the injection rate of the foam on the compressibility of the soil. In these tests the foam is prepared with a Cf = 3% and FER = 10%. The initial water content of the soil is 12% which correspond to the proctor optimal water content. After, the soil is treated with different FIR (50, 80, 110, 150, and 170%).

Fig. 5 shows the soil compressibility curves in these different cases treatment. Increasing the ratio of the foam in the soil leads to the increase of the index of compressibility of the treated soil. It is clear also that the foam causes immediately high increase of the void ratio of the soil. This increase is the result of volume created by the foam bubbles in the soil. Fig. 6 shows the initial void ratio variation of the soil for different treatment.

For the untreated soil, the results showed a compression index C_c=0.113. Fig. 7 shows the evolution of the compressibility index Cc of soil depending on the FIR.

Compressibility index increases quickly to reach a compressibility index equal to twice that the untreated soil for FIR = 150%. This FIR corresponds to the condition of most appropriate treatment for digging deduced from the slump test on the treated soil [4].

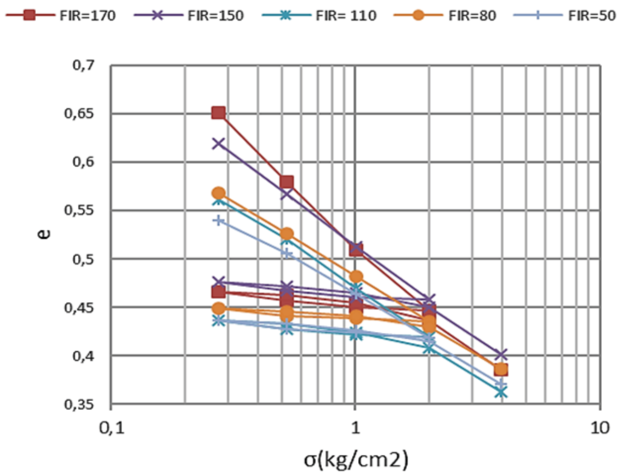

Fig. 5 Compression curve of untreated soil FIR (%)

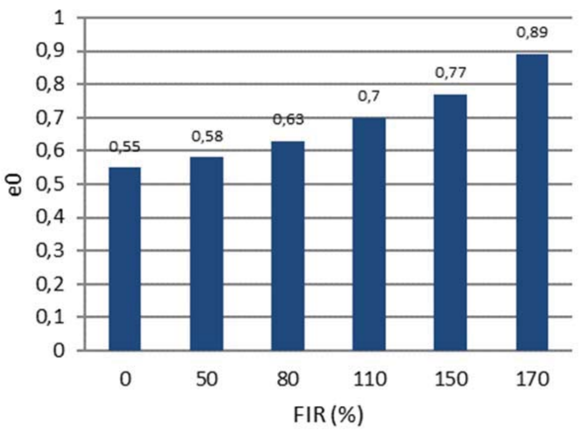

Fig. 6 Void ration variation depending on the FIR

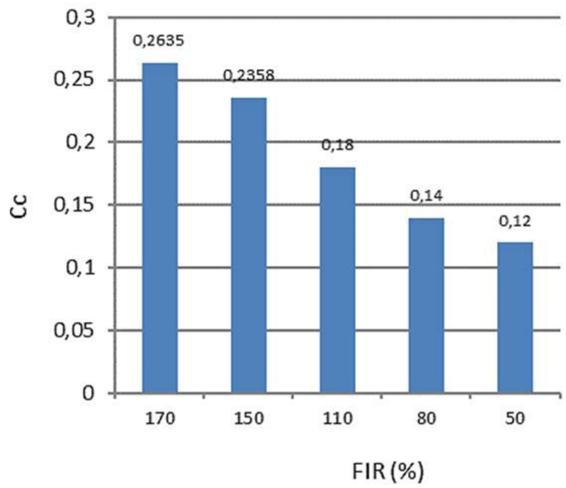

Fig. 7 Compression index variation depending on the FIR

Fig. 8 shows the soil settlement curve under the effect of a load of 27 kPa for tow time; t = 4.5 seconds and t = 5 minutes. It is observed that the soil settlement at t = 4.5 seconds (start loading) varies considerably with the percentage of foam in the soil FIR, while the difference in settlement between t = 4.5 seconds and 5 minutes is not affected by FIR. These results show that the gas bubbles of the foam are instantly affected by the application of load to the ground.

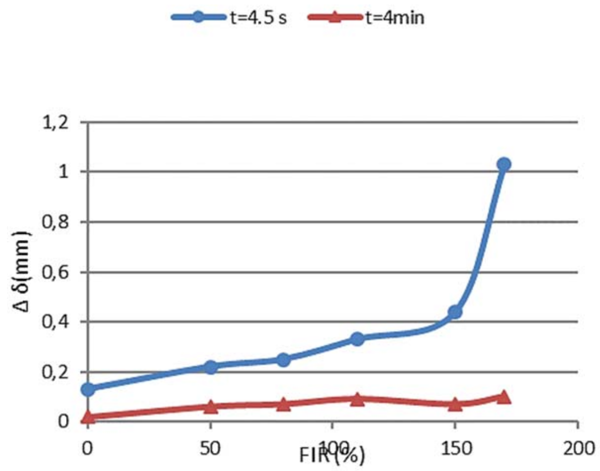

Fig. 8 Effect of loading on the foam

C. Shear Test

Direct shear tests are carried out with the consolidated and undrained condition (CU). The results on an untreated soil give a cohesion Ccu=2.15 kPa and an internal friction angle Φcu=23.2°.

Shear tests were carried out on a soil treated with different FIR to interpret the effect of rate foam injection. Results show that the shear stress decreases with increase FIR (Fig. 9).

This decrease of shear stress reflects the effect of the gas bubbles rates incorporated in the soil. These bubbles of foam are characterized by very low friction and large deformation.

Shear tests with different rates have been also made to interpret their effect on the treated soil shear stress. These tests are carried out on soil treated with Cf = 3% FER = 10% = 150% FIR. Shear rates used are 1.27, 3, and 4.5 mm/min. The test was conducted on soil samples consolidated to a stress of 65 kPa. Fig. 10 shows the deformation stress curves results. These results show that the shear stress decreases with increasing shear rate of the treated soil. It may interpret the viscoelastic behavior of the foam which tends to reduce shear stress by increasing the rate.

D. Permeability Test

Reduction of soil permeability at the face of TBM minimizes the possibility of face collapse due to water inflow. In the clay soil, the aim is to form the rubble of intact blocks, in a matrix of foam which inhibits uptake of water by the clay. The gas bubbles formed by the foam play this role by occupying the void between the soil particles and thus reduce the rate of water flow [4].

The untreated soil consolidated at 53 kPa presents a value of permeability equal to kw= 3.32 10^{-9} m/s.

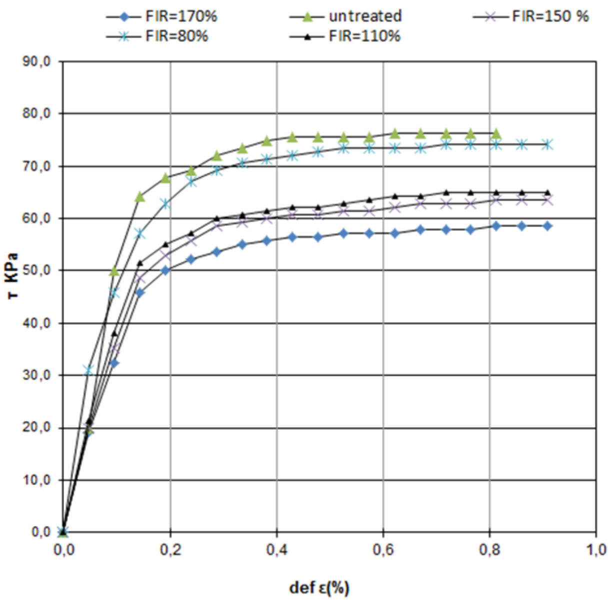

Fig. 9 Curves shear stress vs. horizontal deformation with different FIR (σ_N=148 kPa)

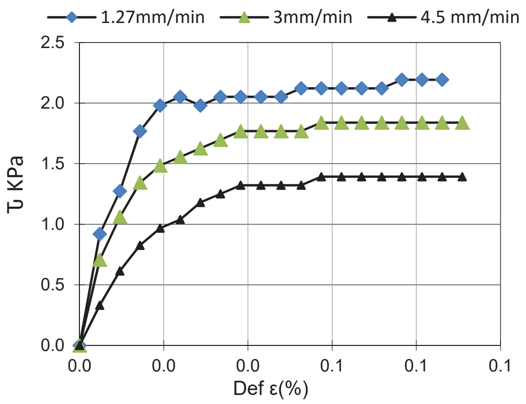

Fig. 10 Effect of the shear rate in the treated soil shear stress

TABLE II
PERMEABILITY TESTS

Test N°	Permeability (m/s)	Conditions
1	3.32 10^{-9}	Untreated soil, $\sigma = 53\ KPa$
2	9.85 10^{-10}	Treated soil, $\sigma = 53\ KPa$
3	2.08 10^{-9}	Treated soil, $\sigma = 100\ KPa$

A test on the treated soil (Cf = 3%, FER= 10% and FIR=150%) with the same characteristics as the untreated soil (consolidated at 53 kPa) provides a permeability equal to 9.8510^{-10} m/s.

The same test on the consolidated Treated soil at a stress of 100 kPa gives permeability equal to 2.0810^{-9} m/s. This permeability is close to the permeability of the untreated soil and confirms the effect of loading on the crashing foam incorporated into the soil.

IV. CONCLUSION

This study is devoted to characterize the property changes of treated sandy clay soil with foam agent. The performed experiments investigate the evolution of mechanic and hydraulic properties of the soil model at different ratio of the foam in the soil. Precisely, the permeability, mechanic oedometric properties and the soil friction angle are examined.

Through this experimental study, several findings are revealed. The hydro-mechanical characteristics are connected to the foam properties incorporated into the soil. The treated soil can be considered as a composite matrix that combines both behavior of the foam and the untreated soil. A next step of this work is to deduce analytically through the homogenizations formulations for the behavior of such materials.

The easy degradation of the foam under the effect of a load or when it is exposed to atmospheric pressure makes it possible to treat the excavated soil to reach their initial hydro-mechanical properties and reuse it in other civil engineering project.

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