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Keywords

Conditioned soil, Foam, Degradation, Compressibility, Excavation, Mining

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Compressibility Behavior of Conditioned Sandy Clay Considering the Physical Degradation of Foam: Tunneling Issue

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Abstract

Surfactants in the form of liquid foam are commonly used for ensuring the fluidity of conditioned soil during shield tunneling in mining zone. The compressibility can be significantly affected, depending on the percentage of fine soil. Thus, this paper investigates the compressibility of foam-conditioned fine soil. Oedometric tests as a function of the percentage of foam have been performed. Foam's stability was analyzed, considering a laboratory soil made from 40% kaolinite and 60% of sand and mixed with a foaming agent based on an anionic surfactant. Experimental results showed that the foam stability was manifested through a reduction of the foam's volume followed by liquid drainage, under loading and due to the foam's physical degradation over time. The compressibility increases with the adding rate of the foam in the soil. Therefore, consolidation and foam's degradation over time are two factors that allow the recovery of the compressibility property of conditioned soil.

Keywords: conditioned soil, foam, degradation, compressibility, excavation, mining

1. Introduction

During tunneling with an earth pressure balance (EPB) shield in the close mode requires liquid or foam to be added (see, for instance, [1]). Adding foam in the opening excavation acts as a lubricant agent and facilitates the tunneling. In fact, surfactants in the form of liquid foam are commonly used for ensuring the fluidity of conditioned soil and reducing the potential sticking of clay in the first stage of cutting head and during transportation of the extracted soil to use outside of excavated zone. Obviously, the environmental aspect linked to the reuse of the conditioned soil is of high interest, not only in mining excavation works but also in tunneling for civil engineering works.

Several factors significantly affect tunneling performance [2], such as the clogging of clay. Thewes and Hollman (2013) [1] summarized the influence relevant to the tendency of soil to cause clogging and presented a classification diagram using the physical properties of conditioned soil, mainly the plasticity and consistency index.

The control of the water content remains a serious practical problem in excavation engineering operations in many fields (mining excavation and infrastructure tunneling). For more details, we can refer to [1,3–6]. Such soils require additives having the capability to reduce clogging and the consequences of sticking. The conditioned soil must also be easily transported by extraction screws, especially in mining excavation, where this second stage is also so important.

Most previous studies have focused on the effect of foam on soil properties (physical and mechanical properties) without considering the degradation and evolution of the bubbles [7,8]. In fact, the physical properties of the foam change over time (reduction of the bubbles' dimensions and gradual disappearance of the film) under both the chemical potential and mechanical loading.

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The space occupied by the foam does not have a fixed geometry, unlike the standard case of a porous medium [9]. In fact, the bubbles deform and partially disappear when the fraction of liquid and pressure change [10–12].

This complex phenomenon is studied in this paper by examining foam stability according to two different aspects, defined as physical and mechanical stabilities. Due to the complexity of conditional natural soil studying, for which several variable parameters have interfered, laboratory soils were chosen.

Tests were performed using oedometric cells with various foam rates. Adding to that, some micro-investigations of the conditioned soil have been carried out by optical microscopic using different foam rates. When the bubbles disappear, the drainage volume of liquid has been used as a parameter to analyze the role of foam degradation. Micro-investigations were used to 1) explain the effect of foam on the soil structure and 2) give an answer about gas bubbles distribution in the soil matrix after immediately the mixing phase considering the loading.

2. Overview of foam and foam-soil mixing stability

Foam is defined as a dispersion of gas bubbles in a liquid. The dimensions of the bubbles are in the colloid size range [1–1000 μm], [7]. Due to the degradation of the foam bubbles, the foam has an evolving character, even over a short duration. Foam stability is governed by coarsening, coalescence, and drainage [8,13–16]. These three factors are frequently coupled and involved simultaneously. It has been noted that they are expressed differently in the case of foam mixed with soil [17]. The presence of the foam in the soil modifies the structure of the soil by adding bubbles of gas surrounded by a thin liquid film to the soil matrix.

The mineralogy and grain size distribution play an important role in developing sticky behavior that results in wettability in some cases or clogging in other cases. In fact, the non-cohesive soils cannot clog and become sticky, while adding foam significantly reduces the friction mobilized between grains of such soils. However, for cohesive soils mineralogy plays a fundamental role because it is a key to facilitate and promote clogging. It was shown that the more the plasticity index is, the more the clogging risk happens. It is the case, for example, for montmorillonite which is due to its intracrystaline swelling, its clogging potential is highest [1]. In the other hand, it was demonstrated that the evolution of foam over time depends on the foam's structure and the applied external pressure. Understanding the physical and mechanical mechanisms of the foam permits to characterize the foam life and the foam degradation.

Moreover, the foam was characterized by a permeability related to its surface tension, the viscosity of the solution, and the hydrostatic pressure [18]. This characteristic of the liquid foam gives the advantage of being able to saturate the soil-foam mixture as a composite formed of foam incorporated in the soil matrix.

The response of the foam depends on the applied stress. If submitted to high pressure, bubbles are rearranged, and the foam can flow as a non-Newtonian viscous fluid. If the applied stresses are low, the bubbles are deformed, which increases the area of liquid/gas interfaces (see, e.g., the review work of [15,19].

Experimental tests carried out by [20] have revealed a semi-empirical relation that expresses the yield stress σ_s as a function of the mean radius of the foam bubbles R:

$$\sigma_s = \alpha_y \frac{T}{R}(\phi - \phi_c)^2 \tag{1}$$

where ϕ is the gas volume fraction in the foam, α_y is a constant between 0.5 and 1 depending on the foam quality, T surface tension, and $\phi_c = 0.64$ gas volume fraction, which limits the elastic behavior of foam.

Wu et al. (2018) [15] studied the microscopic and macroscopic evolution of only foam, confined in a chamber and subjected to different pressures. Their results showed that the bubbles were compressed and rearranged to give smaller bubbles with reduced volume. The evolution of the bubble diameters is important at the beginning of each loading. When the pressure reaches 2 bars, the bubbles become quasi-incompressible in the liquid, with a much smaller deformation. The evolution over time of the foam shows that the bubbles under significant pressure evolved less rapidly than the bubbles at atmospheric pressure. The evolution over time is reflected by the phenomena of coalescence and drainage, which lead to the increase in the size of the bubbles and the weakening of the liquid film protecting the bubbles. The bubbles crash when the liquid film becomes extremely thin and the pressure in the bubbles equals atmospheric pressure.

In soil-foam mixing, the soil particles prevent the evolution of the foam due to the low porosity, which increases their stability compared with foam alone [7]. Solid particles can be used to increase foam stability [19]. Fameau and Salonen (2014) [19] showed that drainage is strongly slowed down by the presence of the particles, as they can start aggregating in the foam network. Surfactants serve to minimize the interaction between the fine particles and the bubbles, and thus, they avoid crushing the bubbles. These surfactants constitute the liquid film that protects the bubbles. Nanoparticles are usually used to establish foam stability and ensure that the different types of industrial foam can be used for as long as possible [21]. Consequently, the foam is used by the EPBs to facilitate the digging operation, and the soil particles mixed with the foam during the excavation procedure provide foam stability. Finally, the evolution of the compressibility and several other mechanical properties of the excavated soil depends on the evolution of the injected foam.

In the case of conditioned sand, the foam in the soil is considered a two-phase system, where the interstitial pressure depends on the pressure on the foam. Hajialilue-Bonab et al. (2014) [8] considered stable foam's gas bubbles with higher pressure than that of water. If the water pressure became greater than the pressure in the bubbles, the bubbles became deformed and partially crushed, resulting in a foam liquid production. In addition, Psomas (2001) [7] showed that the compressibility and shear of the soil-foam mixture were highly affected by the foam bubbles' deformability.

Peila (2014) [2] studied different cases of clay soil characterized by different initial natural moisture water content. The author has demonstrated that based on the slump test, a well-conditioned slump was obtained with low initial water content, small percentage of lubricating polymer (concentration = 0.1%), and standard foam. However, these percentages are still not really fixed and depend significantly on the plasticity of the soil. From a practical point of view, the authors pointed out that the use of a foaming agent was necessary to give the conditioned soil the desired consistency to properly transmit the pressure and decrease soil permeability.

However, in coarse granular soils, the advantages of a foam agent use in EPB tunneling are the reduction of friction, and, therefore, the reduction of the driving torque which results in the reduction of the wear and tear of the cutter [22–24]. Psomas (2001) [7] investigated the effect of foam on compressibility and soil shear from oedometric and Casagrande shear box tests on sandy soil. The author showed the friction angle reduction and the increase of the compressibility coefficient.

Recently, Peila (2014) [2] studied clay samples constituted by clay clumps and powdered material, conditioned by foam with and without polymers. The author mentioned that, for conditioned soils, the stiffness vanished at small strains and increased again at higher strains. It was also demonstrated that the use of a standard foaming agent was necessary to give the conditioned soil a desired consistency, necessary for excavation. However, for the clay with high plasticity (40–50%), the author showed a beneficial role of the added polymers with foam compared to only foam, which led to an effective and useful mixing.

Since state of the art established by Milligan et al. (2000) [3] about the performance of conditioning soils, many laboratory tests using newly developed devices to study the foam behavior alone and its mixing with soils have been developed [23,25–28]. In the same sense, other authors have developed reduced models of tunneling [2,29,30] and studied, particularly, the choice of optimal conditioning amount and the role of the type of conditioning product. The positive effect of the optimum conditioning parameters on the efficiency of the screw conveyer was shown from the effect on the tank cell pressure, the screw conveyor cell pressure and the torque meter on the screw evolution (see, for instance [29]). Results showed that the pressure in the tank, using the optimal conditioning material, showed a regular trend of pressure equal to the theoretical value. Considering conditioned dry soil, the measured pressure for the screw torque was higher than the one obtained from the optimum conditioning soil at a field water moisture content (see, for instance Vinai et al., 2018, [26]).

In situ, the choice of foam type and the additive percentage depend mainly on the type of soil and the characteristics of the TBM [31]. Types of additives include special anti-clogging agents to avoid clogging problems, anti-abrasion additives for the cutter head and its tools, as well as for the extraction screw.

Naturally, the evolution of physical, hydraulic and mechanical properties of in situ soil is well complex to study, from the moment when the mineralogy, the presence of water and the GSD of soil are the main factors conditioning the success of adding-foam [7,8]. For the guidelines on the reuse of excavated soils (published by the Swiss Agency for the Environment, Forest and Landscape [32]), the excavated soil was well affected by the conditioning foam and often considered solid waste, which cannot be used in civil works without specific treatment.

3. Experimental study: conditioned soil and foam characterization

3.1. Soils properties

In the first part, three types of soils (A, B, C) were formed by the mixture of clay (Kaolinite: Polwhite KL) and sand (Hostun HN31) at different mass rates in order to evaluate the conditioning performance of the foaming agent on the sandy-clay mixture. The physical properties of the selected soils are summarized in Table 1.

Figure 1 shows the grain size distributions (GSD) of the selected soils. As can be observed in Fig. 1, these "soils models" are classified as fine soils which need conditioning with foam during the digging process using an EPB machine (according to the chart published by [33]). On the other hand, according to the diagram presented by [24], risks associated with soil conditioning can be empirically evaluated based on limit liquid (W_l), plastic limit (W_p) and natural water content (W_n). Depending on the natural water content in the range of 0–30%, and using the chart presented by [1], the structure's state of soils A and B varied from very stiff structure to very soft structure, which can present a risk of clogging. Consequently, as we can have expected, adding foam potentially will reduce the soil viscosity. However, for soil C, the risk of clogging can be neglected. Then, in this case, the role of adding foam is considered only to improve its workability and to reduce its permeability during excavation. Otherwise, despite the need for foam, the objective of this paper is limited to measuring the effect of foam adding on the compressibility of retained soil type.

In this experimental study, all the samples, from soil A, B and C were prepared at a fixed initial water content corresponding to the optimum moisture content obtained by standard Proctor tests (AFNOR NF P-94-093).

3.2. Performance of foam conditioning agent used in soils

Firstly, a generation of foam was done according to the following methodology: Firstly, 100 mL solution was prepared in a graduated container with a concentration of surfactant $C_f = 3\%$. Then, this solution was mixed with a stirrer at a speed of 2000 rpm to reach a foam of $FER = 10$ (foam volume = 1 L in a graduated container).

Although, habitually the slump cone test is performed on fresh concrete. It has also been widely used in the tunneling industry. It provides a simple and quick procedure for quality control, both in the laboratory and on the working site during mining excavation and tunneling [26,34]. The typical test procedure is as follows (ASTM 143C): The soil is mixed with the desired amount of foam and water in a mixer, and then poured into slump cones. After 1 min without stroking or mixing the soil, the cone is lifted. The fall value and global behavior of the mix are then observed [26]. Guidelines for foam injection ratios based on experience from job sites were published by the European Federation of Specialist Construction Chemicals and Concrete Systems [31]. Three parameters were defined and summarized, as follows [24,35]:

- foam injection ratio *(FIR)*

$$FIR = \frac{V_F}{V_{CS}}\ (\%) \tag{2}$$

- foam expansion ratio *(FER)*

$$FER = \frac{V_F}{V_L} \tag{3}$$

- surfactant dosage (C_f)

$$C_f = \frac{V_{st}}{V_{st} + V_w}(\%) \tag{4}$$

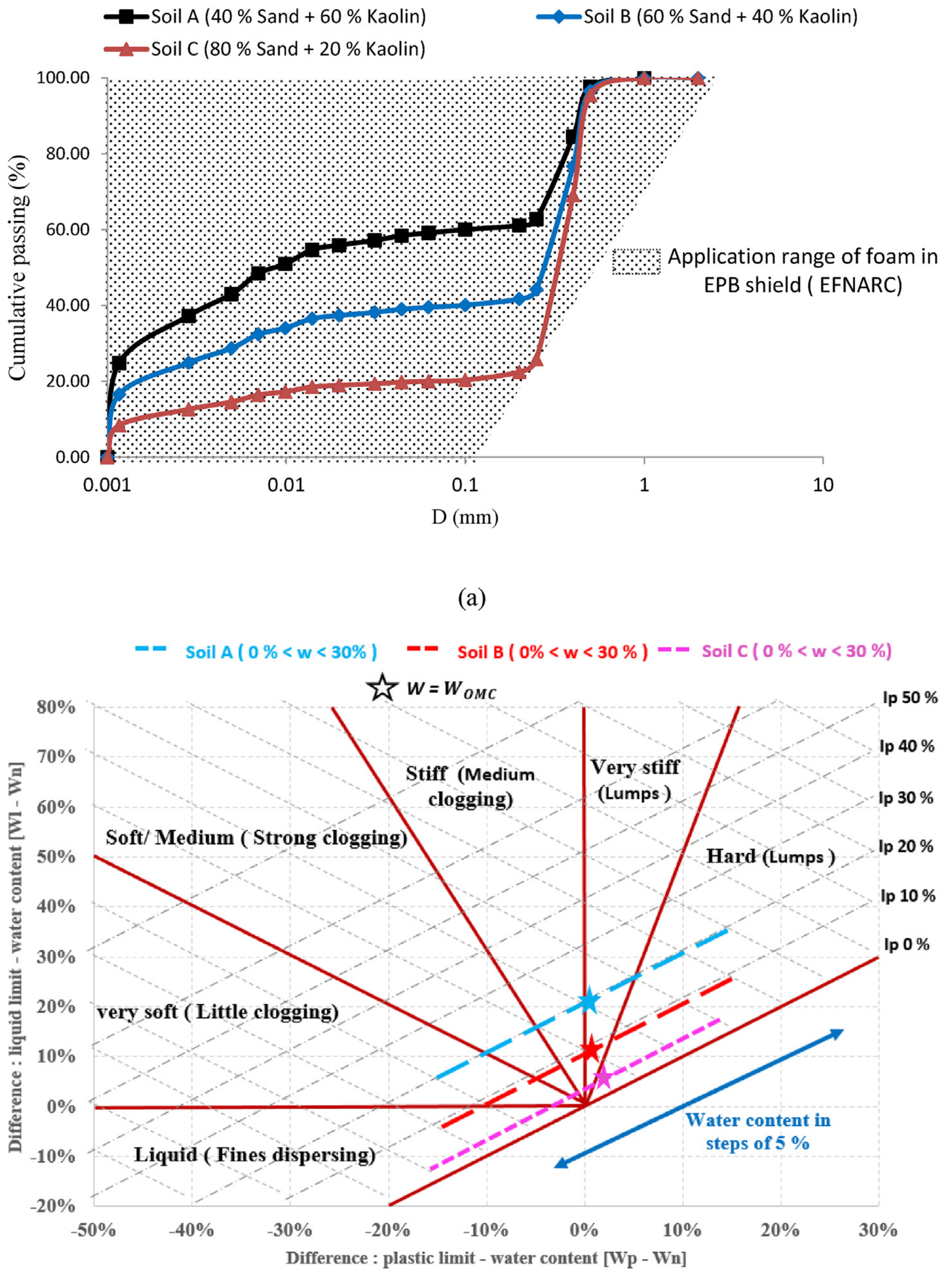
where V_L is the surfactant solution volume, V_F is the foam volume, V_{cs} is the conditioned soil volume, V_{st} is the volume of the surfactant, and V_w is the volume of water. *FER* and C_f define the quality of the foam produced, while *FIR* is a rate which defines the quantity of foam injected into the soil.

Extensive studies have been carried out to investigate foam viscoelastic behavior (see, for instance, [20]).

The selection of the foam type and the additive depends mainly on the type of soil and the characteristics of the TBM. In this study, CLB F5™/AC foaming agent was chosen to condition a sandy-clay soil. As represented by the supplier company (CONDAT), a foaming agent is used in order to reduce the adhesion of clay to tools, to reduce tool wear and replacement frequency. It is also largely preferred to avoid the costly use of the polymers and the resulting pollution risk of soil and watertable. The produced foaming characteristic is influenced by the surfactant concentration C_f and foam expansion ratio *FER*. In this study, C_f of 3% and *FER* equal to 10 were used for generating a foam with the properties recommended by excavation companies ([7], see Fig. 2). The C_f and *FER* values were kept the

Table 1. Geotechnical main data of soils used for tests.

	Soil A	Soil B	Soil C
Sand (%)	40	60	80
Kaolinite (%)	60	40	20
Solid specific weight (kN/m^3)	26.75	26.5	26.7
Liquid Limit w_l (%)	28.54	22.90	17.1
Plasticity limit w_p (%)	16.84	15.4	14.6
Optimum moisture content W_{op} (%)	15.5	12.3	10.8
Permeability (m/s)	$6.67 \cdot 10^{10}$	$3.32 \cdot 10^{-9}$	$8.7 \cdot 10^{-7}$



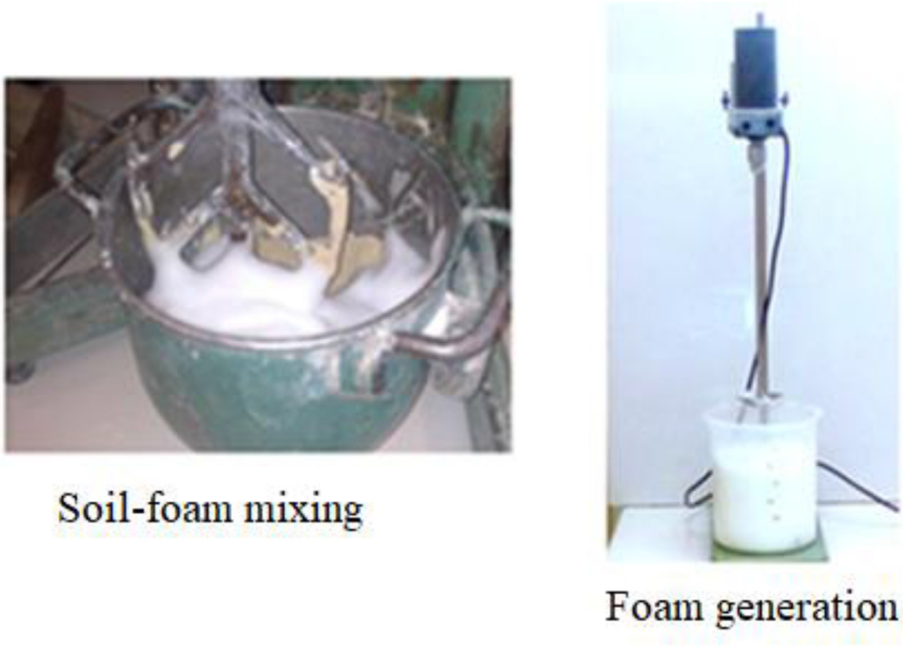
(a)

(b)

Fig. 1. Evaluation of the risk in conditioning soil; a) particle size distribution curve of the used soils and application range of EPB tunneling, b) classification diagram to evaluate the clogging of soil [1].

same for all tests, while different *FIR* values were considered.

Mixing the foam with the soil is ensured using a cement paste mixer (Fig. 2). The mixing operation is stopped when the foam is perfectly homogenized with the soil. Typically, the mixing process takes 3 min to check the integration of the foam's gas bubbles into 2 kg of soil. After this, a series of slump tests were carried out using a mini-slump cone (height, $H = 15$ cm; bottom cone diameter, $D_1 = 10$ cm; upper cone diameter, $D_2 = 5$ cm). Typically, the value of an adopted slump cone is in the range of 3–6 cm to satisfy the conditioned soil workability. Evidently, this range does not depend on the type of surfactant, and it allows for maintaining a condition that is neither too fluid nor too



Soil-foam mixing

Foam generation

Fig. 2. Mixing process of the sample soil with foam.

stiff [30,34,35]. The variation of the slump value according to the *FIR* percentage was carried out (Fig. 3). The results of slump tests showed a slump value varied in the range of 3–6 cm, for *FIR* values of 140–160% for soil types A and B. However, soil C requires a lower *FIR* value of 90–120% to satisfy the desired consistency in the EPB machine. An *FIR* value of 150% was chosen as the optimum value for obtaining more adequate soil properties during excavation in EBM tunneling. (It was also selected following EFNARC, 2005).

Aiming to reserve this study to the soils having the clogging risk, only compressibility of soil has been the interest of this paper. In addition, this paper focuses on the role of main parameters such as *FIR*, external loading and physical degradation over time. Consequently, only the results concerning soil B as a "soil model" are presented here. The efficiency of adding foam in terms of degradability and evolution of the mechanical properties as a function of lifetime of the foam was investigated, and the associated results are discussed in the following.

3.3. Physical characterization of the conditioned soil B and evolution of the foam concentration during the mixing procedure

The *FIR* parameter defines the volume percentage of the foam injected into the selected "soil model" before the kneading operation. This mechanical operation can lead to the degradation of a significant part of the foam. Thus, a parameter S_g has been defined for associating the *FIR* parameter with the volume percentage of the foam in the soil after the conditioning operation. In this study, this parameter was measured in the case of saturated samples with a total volume of V_t, expressed as

$$S_{g,0} = \frac{V_{g,0}}{V_t} \tag{5}$$

where $V_{g,0}$ is the volume of the foam gas bubbles generated in the soil after the conditioning procedure under atmospheric pressure. The foam's gas bubbles are considered "particles" with different properties than those of solid particles. The measure of the volume of the foam bubbles involves saturating a total volume of the soil-foam mixture (V_t) with weight W_t with water. After being kept in an oven for 24 h at 105°, the weight of the dry sample is measured.

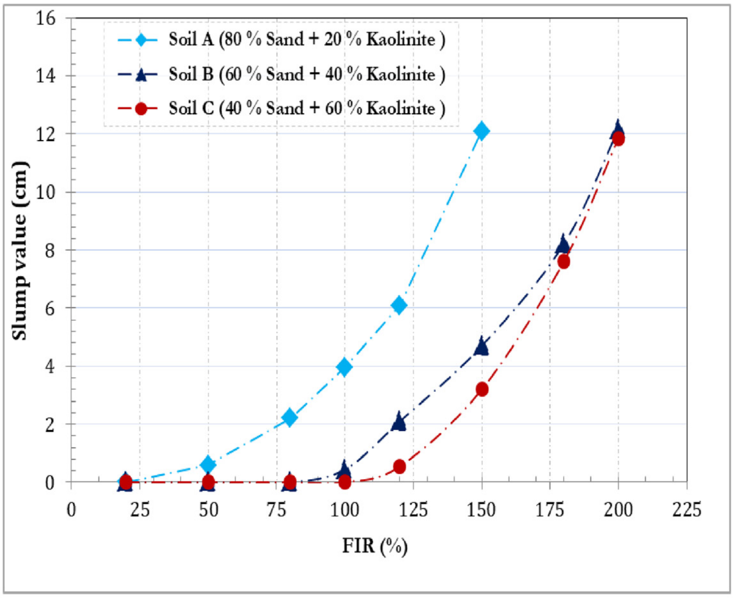
The total volume of a saturated soil-foam mixture is given by Eq. (6):

$$V_t = V_s + V_w + V_g \tag{6}$$

After oven drying, the weight of the water phase (W_w) and the solid weight (W_s) were deduced, assuming the weight of the gas bubbles covered by the liquid would be negligible. Next, V_s and V_w could be computed by Eq. (7) and Eq. (8), respectively:

a) Not suitable : mixture too fluid

b) Not suitable : mixture too dry c) Suitable mixture



(d)

Fig. 3. Influence of foam addition on the slump behavior of soil (mini-slump test) (from a) to c) slump test procedure (d) slump value function of FIR for soil A, B and C.

$$V_s = \frac{W_s}{\gamma_s} \tag{7}$$

$$V_w = \frac{w_w}{\gamma_w} \tag{8}$$

where γ_s and γ_w represent the density of the solid grains and the density of the water, respectively. Finally, the sum $V_{g,l}$ of the foam volume and foam liquid was deduced using Eq. (9):

$$V_{gl} = V_t - (V_s + V_w) \tag{9}$$

The results show a zero S_g for *FIR* less than 50% due to the total degradation of the foam during the kneading operation (Fig. 4). Following this, a linear generation of bubbles of the foam function of the initial foam concentration was demonstrated.

3.4. Micro-investigation of conditioned soil after mixing (optical microscope − OM-observations)

Injected into the soil, the foam bubbles are distributed throughout the matrix randomly. These bubbles influence the specific weight of the soil. The

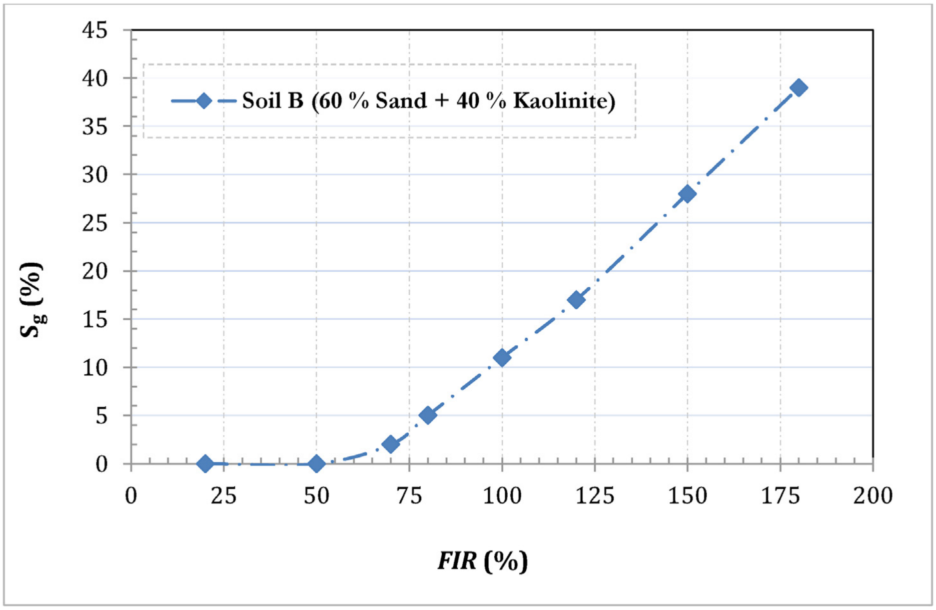


Fig. 4. Evolution of the volume percentage of foam gas bubbles in the soil (S_g) as a function of FIR.

volume of bubbles in the soil-foam mixture varies as a function of the *FIR*. Optical microscope observations were carried out (Figs. 5 and 6). The microscope used was an Axio Imager (ZEISS, France), with image processing performed using the AxioVision software. Because the particles of kaolin are much smaller than the average size of sand grains (Fig. 5 a, b), the kaolin particles are more distilled in the mixture, and the overall density of the materials tends toward that of kaolin, which is more significant compared with the density of sand. Figure 5b shows that the grains of sand were locally included in the dry clay and randomly distributed with a low volume percentage. In the humid case, the clay particles attached and covered the sand particles due to the intergranular cohesive forces; mainly, the clay particles were observed on the sample surface.

The effect of foam on the conditioned soil structure was analyzed by microscopic observations on conditioned sand alone, conditioned kaolin, and the conditioned sand-clay mixture. To clearly observe the foam in the soil, the observations were made on the conditioned sample with the retained value as an optimal *FIR* (*FIR* = 150%). Different observations were conducted under the same conditions at atmospheric pressure (without any loading). The samples were prepared for an *FIR* of 150%, and the observations were made just after the mixing operation to avoid a large number of bubbles being crushed over time. In the case of conditioned sand, foam gas bubbles occupied the intergranular pore by adapting their shape and size (Fig. 6a). The foam gas bubbles' diameter was similar to the sand particle diameter. In the case of conditioned kaolin, the foam was distributed in the matrix as spherical inclusions with different sizes. The size of the bubbles was generally lower than in the case of the foam in the sand. In addition, in the case with the

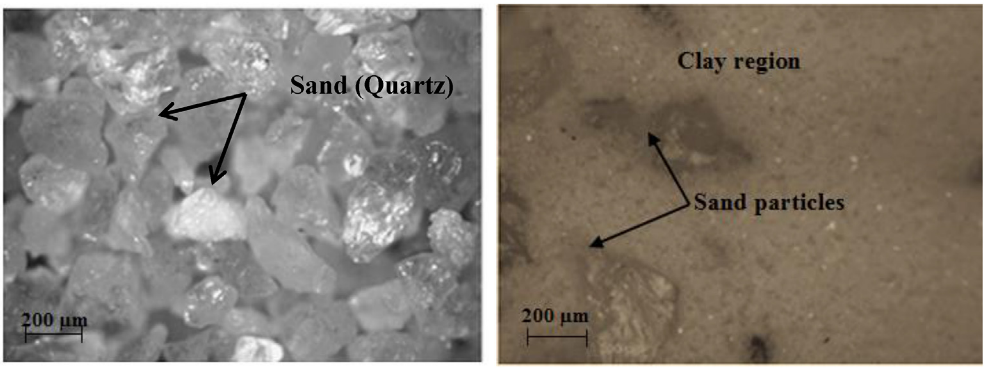


Fig. 5. Photos of (a) dry sand (5 × magnification), (b) dry sand-clay mixture, 40% kaolin +60% sand (10 × magnification).

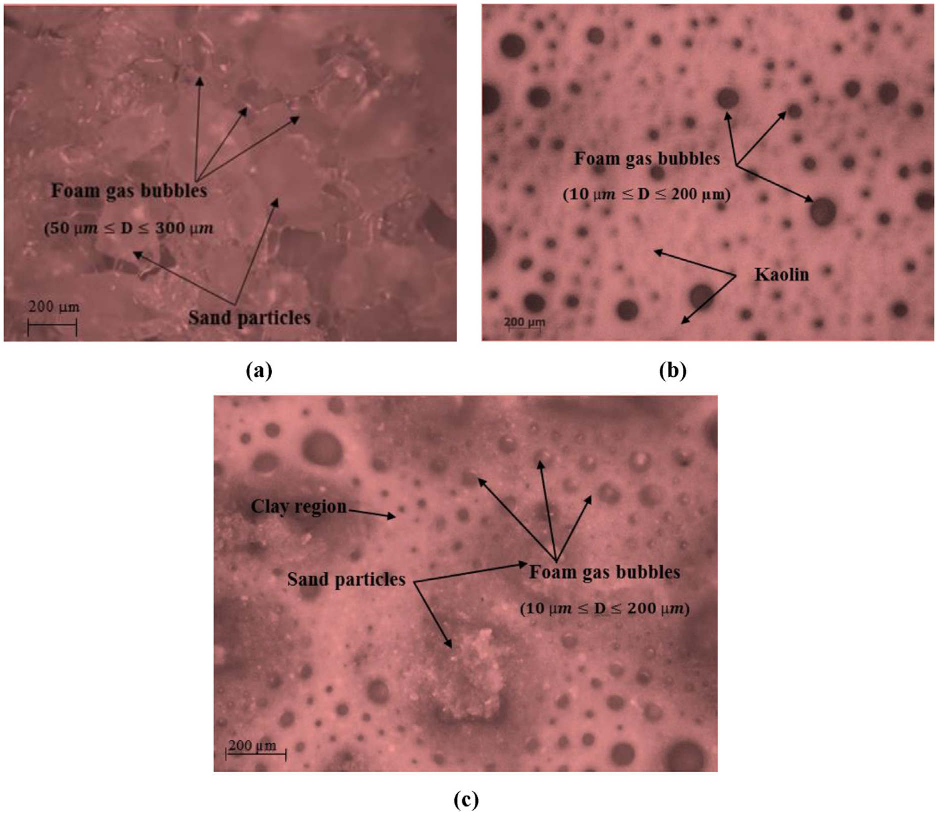


Fig. 6. Effects of foam on soil structure (D: foam gas bubble diameter): (a) conditioned sand (FIR = 150%, 5 × magnification), (b) conditioned kaolin (FIR = 150%, 5 × magnification), (c) conditioned sandy-clay mixture (FIR = 150%, 10 × magnification).

disposition between the sand grains, the foam bubbles were larger than those distributed in the kaolin mixture (Fig. 6b). For the sandy-clay mixture, the foam was principally distributed in the clay part (Fig. 6c). In the conditioned soil type, the undissolved gas bubbles of the foam were considered as a discontinuous porosity distributed in a saturated soil matrix. In fact, as it was mentioned in the previous works published by [36,37], "the gas bubbles produced by foam are extremely different from the conventional gas, which fits inside the normal void space without affecting the soil skeleton. The foam is distributed in the soil mixing as air bubbles that are totally covered by an extremely thin liquid film. The bubbles are typically wider than the normal void space in the clay soil and cannot be considered occluded in the pore-water".

4. Results and discussion: compressibility of the conditioned soil and the role of the foam's degradation

Oedometric tests were performed on soil B conditioned with different percentages of *FIR* on cylindrical samples of 72 × 20 mm in size (Fig. 7).

Naturally, this set of tests was also performed on saturated samples without foam mixing. Foam injected into the soil first affected the initial void ratio of the soil due to the foam gas bubbles created in the soil. In fact, the initial void ratio varies from 0.54 for unconditioned soil to 1.15 for soil conditioned with *FIR* = 150% (Fig. 8a). This important increase in the initial void ratio was confirmed by the microscopic observations, which showed a large volume of foam gas bubbles inclusions distributed in the matrix as a function of the foam's rate. The evolution of dimensions of gas bubbles during the consolidation affected the compressibility of the conditioned soil.

Oedometric results show a significant effect of the *FIR* on soil compressibility. A large variation in soil compressibility depending on the *FIR* was observed. Soil compressibility increased by increasing the percentage of *FIR* due to the behavior of the bubbles, which became much more compressible in the mixture.

The compressibility of the foam bubbles is added to the compressibility of the soil. Obviously, for conditioned soil, the compressibility of the mixing depends on the rearrangement of the soil particles

Fig. 7. Photo corresponding to the first step of the sample's disposition before œdometric compressive loading.

and foam bubbles. It was found that the compressibility coefficient (Eq. (10)) increased, and the oedometric modulus decreased as a function of the *FIR* (Eq. (11)).

$$c_c = \frac{\Delta e}{\Delta(lg\,\sigma')} \tag{10}$$

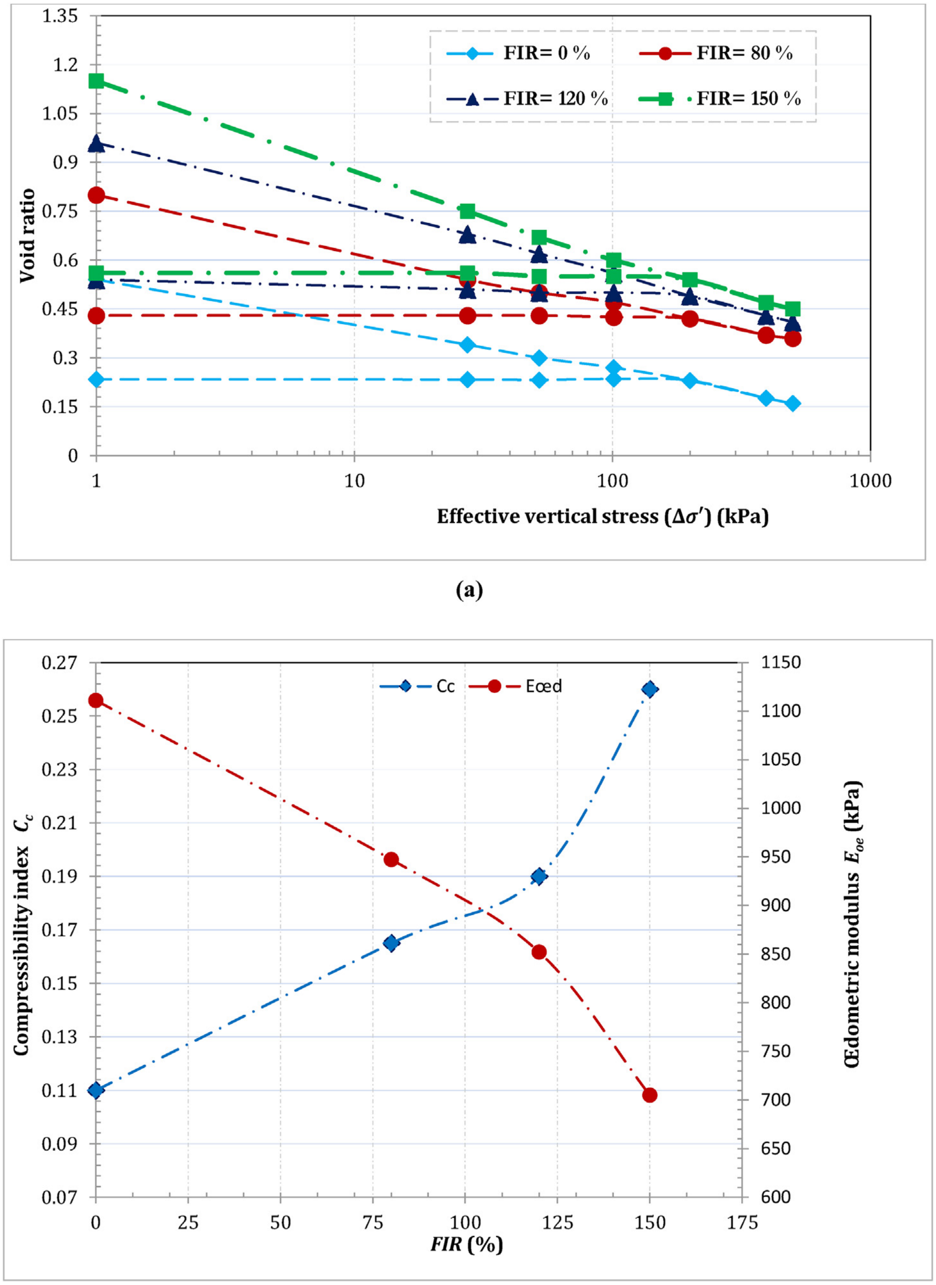
Figure 8b shows the evolution of the drained oedometric modulus function of the *FIR*. The decrease of the oedometric modulus function of the *FIR* was significant. This decrease was affected by the low stiffness of the gas bubbles in the foam incorporated into the soil.

$$E_{\mathrm{oed}} = \frac{\Delta\sigma'\,(1+e_0)}{\Delta e} \tag{11}$$

As shown in Fig. 8b, the consolidation of the bubbles included in the soil first occurred as soon as the load was applied, followed by the consolidation of the soil matrix. The increase in the compressibility index by increasing the percentage of the foam was evidently due to the compressibility of the foam bubbles. This effect of foam on the compressibility index has been confirmed by many previous works [6,7,36].

It is to mention that the drainage of foam-liquid and water was issued by an orifice in the oedometric cell, and the solution (water + generated liquid from the degradation of foam) has been drained. Thereby, the drained foam-liquid volume was evaluated to characterize the stability or the degradation of the foam during the oedometric compressive loading. Otherwise, the bubbles of foam which interact with fine particles and cannot be drained, are reduced in diameter, highly resist applied pressure and remain in the mixed soil-foam.

To link the mechanical response and degradation of the foam bubbles during the consolidation stage (stability evolution of the foam), the evolution of the foam volume percentage under the consolidation stage was measured using the same procedure as in Eq. (9). The decrease in the volume of foam under the consolidation stage showed an important "crushing" or disappearance of the foam bubbles. This volume tended to zero after the loading of 200 kPa (Fig. 9). A relationship between the pressure of the gas bubbles in the foam and the S_g parameter



(a)

(b)

Fig. 8. Oedometric test on conditioned soil (a) Void ratio versus the effective vertical stress (b) Compressibility index and oedometric modulus of conditioned soil.

can be formulated based on Boyle's gas law. In fact, considering an ideal gas law, Boyle's law states that the volume and pressure of an ideal gas at constant temperature are inversely related, as described in Eq. (12). Combining Eq. (5) and Eq. (12) provides the theoretical evolution of the volume percentage of gas bubbles in the conditioned soil, as given in Eq. (13):

$$V_{g,p} = V_{g,0} \frac{P_{\mathrm{atm}}}{P + P_{\mathrm{atm}}} \tag{12}$$

$$S_{g,p} = \frac{V_{g,0}\, P_{\mathrm{atm}}}{V_t (P + P_{\mathrm{atm}})} = S_g \frac{P_{\mathrm{atm}}}{(P + P_{\mathrm{atm}})} \tag{13}$$

where $S_{g,p}$ is the theoretical evolution of the volume percentage of gas bubbles in foam under isotropic

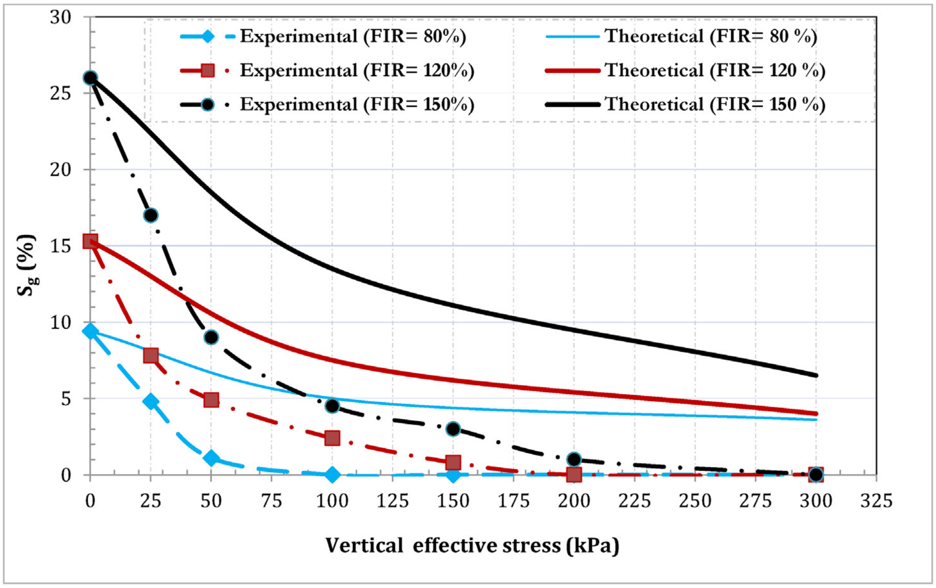
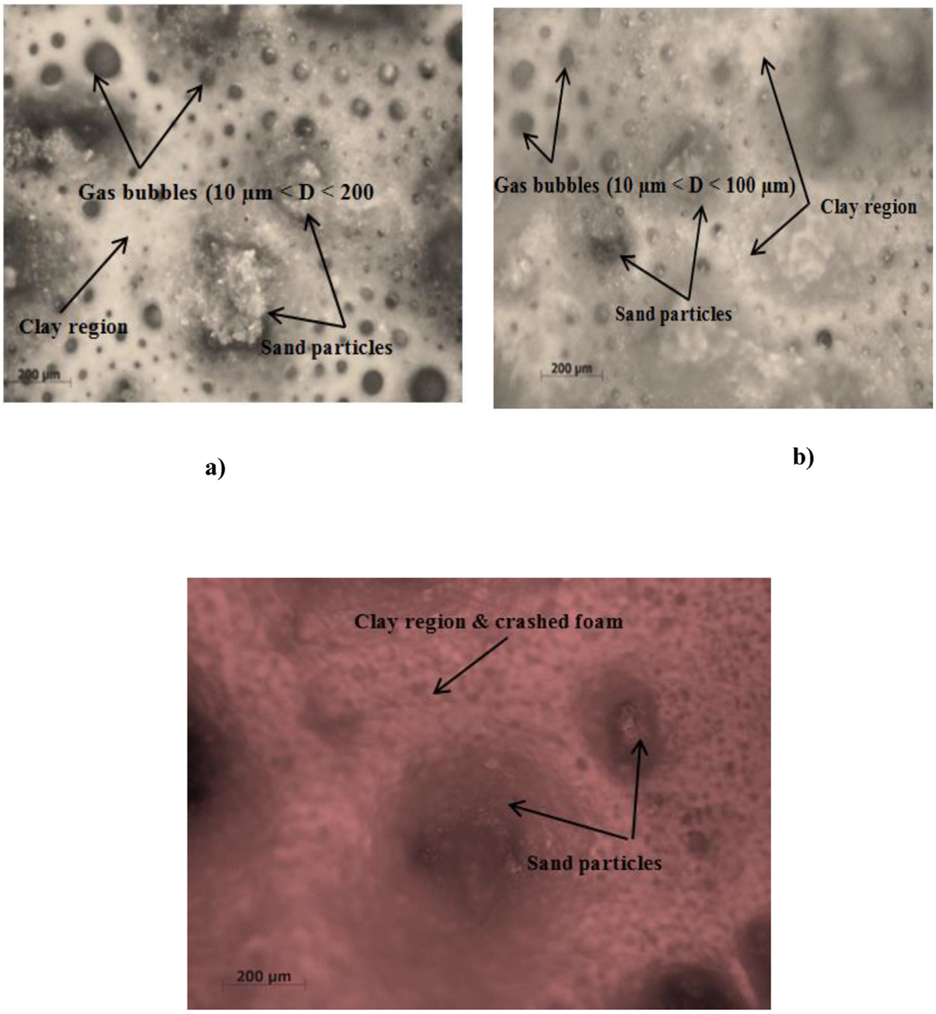


Fig. 9. Evolution of the foam volume percentage under consolidation.



a)

b)

c)

Fig. 10. OM observations of foam structure evolution (FIR = 150%) as a function of vertical stress under oedemetric path: (a) consolidation stress = 0 kPa, (b) consolidation stress = 27 kPa, (c) consolidation stress = 52 kPa.

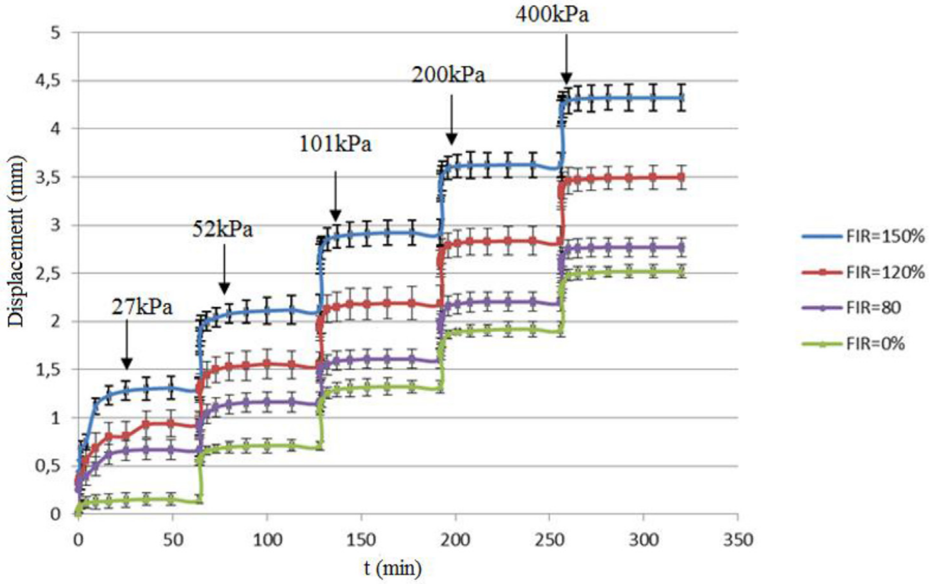


Fig. 11. Consolidation settlement evolution during time for different FIR.

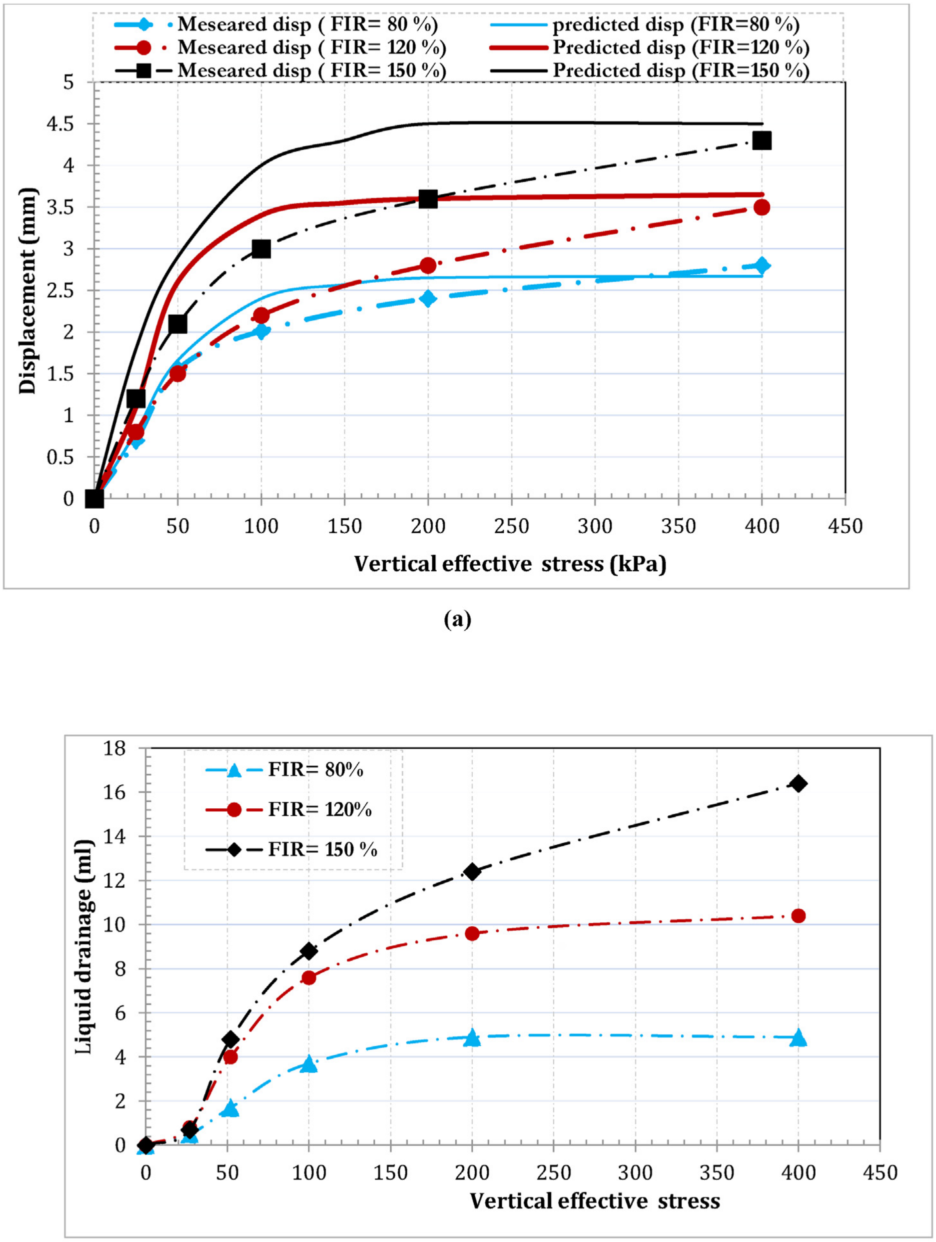
applied pressure P and $V_{g,p}$ is the theoretical volume of gas. At the end of the consolidation state, resulting in zero interstitial water pressure (u_w) in the specimen, the pressure in the foam gas bubbles should incur the effective isotropic stress transmitted to the solid skeleton. Then, during the consolidation, the volume of gas bubbles in the foam changes in such a way that the pressure P tends toward the effective stress. The theoretical evolution of the volume percentage of the foam (parameter $S_{g,p}$) in conditioned soil with different initial *FIR*s was compared with the measured experimental evolution (Fig. 9). The results showed a significant difference between the experimental and theoretical evolutions of foam in the mixture under consolidation. This difference is due to the gas bubbles' disappearance, accompanied by the liquid drainage produced during the consolidation [6,15].

Otherwise, the evolution of foam in the soil under the consolidation stage is similar to the evolution of foam alone under applied pressure, as described by [15]. This results in the “crushing” of the bubbles, with a decrease in the size of the bubbles and the liquid drainage resulting in foam volume reduction. In the soil-foam mixture, the bubbles' “crushing” was more significant due to the rearrangement of the solid particles. The foam volume reduction occurred rapidly under consolidation. Optical microscope (OM) observations of consolidated, conditioned soil ($FIR = 150\%$) showed the bubble distribution for two vertical stresses (Fig. 10a). As shown in Fig. 10b, a significant reduction in the foam volume was observed under the first load applied (27 kPa). It was also noted that the foam bubbles evolved and vanished immediately when they were exposed to atmospheric pressure.

The evolution over time of the settlement shows that the tested samples were instantly compressible, with a significant displacement. Thus, a large settlement of conditioned soil occurred mainly at the first loading increment (27 kPa; Fig. 11). Under loading, the bubbles' volume reduction occurred, and small bubbles were formed. Thus, during the time ΔT, a landing was observed (during ΔT, a cumulative settlement remained constant). In this stage, it seems that the confined small bubbles between solid particles supported the transmitted forces before they disappeared. To ensure the reproducibility of the results, several tests were carried out on different samples with the same *FIR*. The average evolution of the vertical displacement of the mixture according to the *FIR* is represented in Fig. 11.

The deformation of the gas bubbles in the mixture can be expressed as a function of settlement due to the foam volume reduction under consolidation and soil settlement evolution. Considering the settlement of the solid phase under loading as independent of the foam phase, soil settlement in the mixture can be deduced from unconditioned soil settlement and expressed by Eq. (14):

$$\delta_s = \frac{Vs}{V}\,\delta_{\exp} \tag{14}$$



(a)

(b)

Fig. 12. Effect of foam degradation on conditioned soil settlement; (a) effect of the compressibility of foam gas bubbles on the conditioned soil settlement, (b) liquid drainage under the consolidation function of FIR.

where $Vs = V_{\text{soil}}$ is the volume of dry soil in the mixture, and V is the total volume of the mixture.

The settlement due to the foam volume reduction can be deduced from Fig. 12 (Eq. (15)):

$$\delta_f = \frac{V_{a,0} - V_{a,\sigma_v}}{A} \tag{15}$$

where $V_{a,0}$ is the volume of foam at atmospheric pressure and $V_{a,\sigma v}$ is the volume of foam under the applied vertical stress, σ_v. The settlement of the mixture can be deduced from the addition of the two terms (Eq. (16)):

$$\delta_{\text{soil+foam}} = \delta_s + \delta_f \tag{16}$$

Fig. 12a gives the evolution of the experimental settlement of the mixture (δ_{mixture}) compared with the settlement obtained by Eq. (16). The results show a significant difference between the settlement corresponding to the sum of settlements of the two phases and the measured settlement of the mixture.

This difference can be explained by the volume of the liquid drainage generated following the bubbles' volume reduction. Liquid drainage due to this difference is then deduced using Eq. (17) (Fig. 12b):

$$V_{\mathrm{liq}} = \left(\delta_{\mathrm{soil+foam}} - \delta_{\mathrm{mixture}}\right) A \tag{17}$$

5. Conclusion

This study is devoted to characterizing the effect of foam on the compressibility of fine soil. The performed experiments investigated the role of foam volume reduction and liquid drainage. The behavior of the bubbles generated by foam differs when compared to the conventional air encountered in the unsaturated soil thanks to the rheological and hydraulic characteristics of liquid foam.

Through this study, several findings are revealed. Experimental tests on conditioned soil have shown that foam injected in the soil leads to an increase in the compressibility of the conditioned soil due to its high compressibility. From the œdometric tests conducted on the foam alone and on the conditioned soil with different *FIR*, it was shown that the liquid drainage volume can be deduced. The liquid drainage associated with the foam volume reduction implies a decrease in compressibility.

On the other hand, during the time without loading, compressibility reaches its initial value at the final stage of the physical degradation of the foam.

This study opens multiple perspectives. For example, the study must be conducted on natural soil in tunneling and particularly in mining excavation with all its complexity [38]. It is also important to study the chemical degradation of the surfactant and its relationship with this physical degradation of the foam.

The knowledge of the behavior of the soil-foam mixture and their evolution over time allows the control of the embankments coming, eventually, from mining excavation and promotes the possibility of the reuse of soil in other civil engineering works [39].

Ethical statement

The authors state that the research was conducted according to ethical standards.

Conflicts of interest

The authors declare no conflict of interest.

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References

[1] Hollmann FS, Thewes M. Assessment method for clay clogging and disintegration of fines in mechanised tunnelling. Tunn Undergr Space Technol 2013;37:96–106. https://doi.org/10.1016/j.tust.2013.03.010.

[2] Vinai Raffaele, Borio L, Peila Daniele, Oggeri Claudio, Pelizza Sebastiano. Soil conditioning for EPBMs. Tunnels Tunn Int 2008:25–6.

[3] Milligan G. Lubrication and soil conditioning in tunnelling , pipe jacking and microtunnelling a state-of-the-art review. Rev Liter Arts Am 2000;vol. 44.

[4] Filbà M, Salvany JM, Jubany J, Carrasco LA. Tunnel boring machine collision with an ancient boulder beach during the excavation of the Barcelona city subway L10 line : a case of adverse geology and resulting engineering solutions. Eng Geol 2016;200:31–46. https://doi.org/10.1016/j.enggeo.2015.11.010.

[5] Azali ST, Ghafoori M, Lashkaripour GR, Hassanpour J. Engineering geological investigations of mechanized tunneling in soft ground : a case study, East–West lot of line 7, Tehran Metro, Iran. Eng Geol 2013;166:170–85. https://doi.org/10.1016/j.enggeo.2013.07.012.

[6] Mori L, Mooney MA, Cha M. Characterizing the influence of stress on foam conditioned sand for EPB tunneling. Tunn Undergr Space Technol 2018;71:454–65. https://doi.org/10.1016/j.tust.2017.09.018.

[7] Psomas S. Properties of foam/sand mixtures for tunnelling applications. A thesis submitted for the degree of master of science to the University of Oxford. 2001. Michaelmas.

[8] Hajialilue-Bonab M, Hassan S, Adam B. Experimental study on foamed sandy soil for EPBM tunnelling. Int J Adv Rail Eng (IJARE) 2014;2(1):27–40.

[9] Rio E, Biance A. Thermodynamic and mechanical timescales involved in foam film rupture and liquid foam coalescence. ChemPhysChem 2014;15(17):3692–707. https://doi.org/10.1002/cphc.201402195.

[10] Koehler SA, Hilgenfeldt S, Stone HA. Liquid flow through aqueous foams : the node-dominated foam drainage equation. Phys Rev Lett 1999;82(21):4232–5. https://doi.org/10.1103/physrevlett.82.4232.

[11] Koehler SA, Hilgenfeldt S, Stone HA. A generalized view of foam drainage: experiment and theory. Langmuir 2000; 16(15):6327–41. https://doi.org/10.1021/la9913147.

[12] Brannigan G, De Alcantara Bonfim OF. Boundary effects on forced drainage through aqueous foam. Phil Mag Lett 2001; 81(3):197–201. https://doi.org/10.1080/09500830010017079.

[13] Khristov K, Exerowa D, Minkov G. Critical capillary pressure for destruction of single foam films and foam : effect of foam film size. Coll Surf, A Physicochem Eng Asp 2002;210(2–3): 159–66. https://doi.org/10.1016/s0927-7757(02)00377-1.

[14] Eisner MD, Jeelani S, Bernhard L, Windhab EJ. Stability of foams containing proteins, fat particles and nonionic

surfactants. Chem Eng Sci 2007;62(7):1974–87. https://doi.org/10.1016/j.ces.2006.12.056.

[15] Wu Y, Mooney M, Cha M. An experimental examination of foam stability under pressure for EPB TBM tunneling. Tunn Undergr Space Technol 2018;77:80–93. https://doi.org/10.1016/j.tust.2018.02.011.

[16] Sebastiani D, Ochando-Pulido JM, Bavasso I, Di Palma L, Miliziano S. Classification of foam and foaming products for EPB mechanized tunnelling based on half-life time. Tunn Undergr Space Technol 2019;92:103044. https://doi.org/10.1016/j.tust.2019.103044.

[17] Almajid MM, Kovscek AR. Pore-level mechanics of foam generation and coalescence in the presence of oil. Adv Colloid Interface Sci 2016;233:65–82. https://doi.org/10.1016/j.cis.2015.10.008.

[18] Safouane M, Saint-Jalmes A, Bergeron V, Langevin D. Viscosity effects in foam drainage : Newtonian and non-Newtonian foaming fluids. Eur Phys J E 2006;19(2):195–202. https://doi.org/10.1140/epje/e2006-00025-4.

[19] Fameau A, Salonen A. Effect of particles and aggregated structures on the foam stability and aging. Compt Rendus Phys 2014;15(8–9):748–60. https://doi.org/10.1016/j.crhy.2014.09.009.

[20] Cohen-Addad S, Krzan M, Höhler R, Herzhaft B. Rigidity percolation in particle-laden foams. Phys Rev Lett 2007;99(16). https://doi.org/10.1103/physrevlett.99.168001.

[21] Carn F, Colin A, Pitois O, Vignes-Adler M, Backov R. Foam drainage in the presence of Nanoparticle–Surfactant mixtures. Langmuir 2009;25(14):7847–56. https://doi.org/10.1021/la900414q.

[22] Duarte MÁP. Foam as a soil conditioner in tunnelling : physical and mechanical properties of conditioned sands. 2007. https://doi.org/10.1002/geot.201000023.

[23] Peila D, Oggeri C, Vinai R. Screw conveyor device for laboratory tests on conditioned soil for EPB tunneling operations. J Geotech Geoenviron Eng 2007;133(12):1622–5. https://ascelibrary.org/doi/abs/10.1061/%28ASCE%291090-0241%282007%29133%3A12%281622%29.

[24] Thewes M, Budach C. Soil conditioning with foam during EPB tunnelling/. Konditionierung von Lockergesteinen bei Erddruckschilden. Geomech Und Tunnelbau 2010;3(3):256–67. https://doi.org/10.1002/geot.201000023.

[25] Merritt AS, Mair RJ. Mechanics of tunnelling machine screw conveyors : model tests. Geotechnique 2006;56(9):605–15. https://doi.org/10.1680/geot.2006.56.9.605.

[26] Vinai R, Oggeri C, Peila D. Soil conditioning of sand for EPB applications : a laboratory research. Tunn Undergr Space Technol 2008;23(3):308–17. https://doi.org/10.1016/j.tust.2007.04.010.

[27] Salazar CD, Todaro C, Bosio F, Bassini E, Ugues D, Peila D. A new test device for the study of metal wear in conditioned granular soil used in EPB shield tunneling. Tunn Undergr Space Technol 2018;73:212–21. https://doi.org/10.1016/j.tust.2017.12.014.

[28] Wu H, Huo J, Meng Z, Xue L, Xie L, Zhang Z. Load characteristics study with a multi-coupling dynamic model for TBM supporting system based on a field strain test. Tunn Undergr Space Technol 2019;91:103016. https://doi.org/10.1016/j.tust.2019.103016.

[29] Vinai R, Borio L, Peila D, Oggeri C, Pelizza S. Soil conditioning for EPBMs (2008). Tunnels Tunn Int 2008 Dec 1;(DEC):25–6.

[30] Budach C, Thewes M. Application ranges of EPB shields in coarse ground based on laboratory research. Tunn Undergr Space Technol 2015;50:296–304. https://doi.org/10.1016/j.tust.2015.08.006.

[31] EFNARC. Specification and Guidelines for the use of specialist products for mechanised tunnelling (TBM) in soft ground and hard rock. Surry. In: European Federation for Specialist Construction Chemicals and Concrete Systems; 2005 April; 2005.

[32] Jürg Z, Dettwiler J, Zäch C. Reuse of (Soil excavation guideline). 2001. Berne.

[33] Support of the cavity and settlement. Dans Wiley-VCH Verlag GmbH & Co. KGaA eBooks; 2012. p. 25–46. https://doi.org/10.1002/9783433601051.ch2.

[34] Peila D, Oggeri C, Borio L. Using the slump test to assess the behavior of conditioned soil for EPB tunneling. Environ Eng Geosci 2009;15(3):167–74. https://doi.org/10.2113/gseegeosci.15.3.167.

[35] Thewes M, Budach C. Soil conditioning with foam during EPB tunnelling/Konditionierung von Lockergesteinen bei Erddruckschilden. Geomechanik Und Tunnelbau 2010;3(3):256–67. https://doi.org/10.1002/geot.201000023.

[36] Selmi M, Kacem M, Jamei M, Dubujet P. Experimental and modeling of shear mechanical behavior of soil conditioned with foaming agent. Int J Innov Technol Expl Eng (IJITEE) 2019;8(11). https://doi.org/10.35940/ijitee.K1912.0981119. ISSN: 2278-3075.

[37] Selmi M, Kacem M, Jamei M, Dubujet P. Physical foam stability of loose sandy-clay: a porosity role in the conditioned soil. Water Air Soil Pollut 2020;231:251. https://doi.org/10.1007/s11270-020-04598-8.

[38] Oggeri C, Fenoglio TM, Vinai R. Tunnel spoil classification and applicability of lime addition in weak formations for muck reuse. Tunn Undergr Space Technol 2014;44:97–107. https://doi.org/10.1016/j.tust.2014.07.013.

[39] Caracciolo AB, Cardoni M, Pescatore T, Patrolecco L. Characteristics and environmental fate of the anionic surfactant sodium lauryl ether sulphate (SLES) used as the main component in foaming agents foœr mechanized tunnelling. Environ Pollut 2017;226:94–103. https://doi.org/10.1016/j.envpol.2017.04.008.