Tunnelling and Underground Space Technology 92 (2019) 103044

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Classification of foam and foaming products for EPB mechanized tunnelling based on half-life time

Diego Sebastiani[a], Giorgio Vilardi[b,*], Irene Bavasso[b], Luca Di Palma[b], Salvatore Miliziano[a]

[a] Department of Structural and Geotechnical Engineering, La Sapienza University of Rome, via Eudossiana 18, 00184 Rome, Italy
[b] Department of Chemical Engineering Materials Environment, La Sapienza University of Rome, via Eudossiana 18, 00184 Rome, Italy

ARTICLE INFO

Keywords:
Mechanized tunnelling
TBM-EPB
Soil conditioning
Foaming agents
Foam stability
Half-life test

ABSTRACT

During tunnel excavation with Tunnel Boring Machines (TBMs) and earth pressure balance (EPB) technology, conditioning agents are commonly used to modify the physical and mechanical properties of soils so that they are appropriate for the application of the front-face support pressure during excavation. The consistency of the conditioned soil must be stable during the time necessary to advance and install the lining. Hence, a stability analysis of the injected foams is an important aspect. To assess the stability of a foam a classification is proposed based on the results of a standard foam generation procedure and on half-life tests using products from the main suppliers. A further classification of the foaming agents used according to their ability to produce a stable foam in terms of Foam Expansion Ratio is also proposed.

1. Introduction and background

Currently, TBM-EPB technology is the most often used method to perform mechanized tunnel excavation in soil (Adoko et al., 2017; Gong et al., 2012; Repetto and Fidelibus, 2017). New and technologically improved machines and developments on conditioning of excavated soil by foam have made this technology more effective in various geological contexts (Anagnostou and Kovári, 1996; Merritt, 2004; Milligan, 2000). EPB technology is especially employed in urban areas owing to the special challenge to limit surface settlements (Thewes and Budach, 2010; Shen et al., 2014; Miliziano and de Lillis, 2019). The technology requires the treatment of soil injecting chemicals, in the form of foams, to transform the excavated soil into a homogeneous soft paste. Soil conditioning enhances the excavation process, muck transport and disposal. It reduces wear and tear of the excavation tools and, in urban area, permits that the earth pressure is applied properly to the front face (Milligan, 2000, Merritt, 2004). The extension and depth of the induced subsidence basin largely depend on the uniformity of pressure applied to the front face through the earth filling the excavation chamber (Anagnostou and Kovári, 1996).

To avoid any undue pressure drop in the working chamber during excavation and the installation of the lining it is vital that the foam mixed with the soil maintains its characteristics and that the foam injected does not revert too rapidly to liquid. To study the evolution of conditioned soil properties, a first step is the investigation to assess foam stability itself. The half-life test proposed by EFNARC (European Federation of National Associations Representing for Concrete) (EFNARC, 2005), a very simple and universally accepted experimental methodology to measure foam stability, has been widely adopted. This measures the so-called half-life time (*hlt*), that is the time required by a foam to drain 50% of the weight of the initial conditioning liquid used in foam generation. On this topic, several studies were performed with specific reference to the mechanized tunnelling application by Thewes et al. (2012) and Wu et al. (2018). Major factors affecting foam stability were identified, including the type of foaming agent and its Concentration Factor (*Cf*), the Foam Expansion Ratio (*FER*), the type of foam generator used and the values of the injection pressure. The effects of different foam generators and the addition of special polymers to improve foam stability were investigated by Mori et al. (2018). Foam stability is also studied in the field of chemistry and chemical engineering (Wang et al., 2017) and the bubble stability is defined as a function of the size and uniformity of the bubbles and of the strength of the bubble wall. Variations in the conditioned soil properties over time is regulated by other factors: (i) soil properties (grain size, mineralogical composition); (ii) characteristics of the foam (chemical composition), its dosage and chemical biodegradation (Vilardi et al., 2018); (iii) temperature and pressure conditions within the excavation chamber (Tokgöz et al., 2015); (iv) features of the soil outside the TBM such as permeability (Liu et al., 2019).

Despite the large number of studies on this topic, a foam

* Corresponding author.
E-mail address: giorgio.vilardi@uniroma1.it (G. Vilardi).

https://doi.org/10.1016/j.tust.2019.103044
Received 24 March 2019; Received in revised form 21 June 2019; Accepted 19 July 2019

classification based on its stability is still lacking. Thus, the aim in this study is to cover this lack by proposing a classification system of the stability of a foam based on *hlt*. A further classification of the foaming agents used based on their ability to produce a stable foam is also proposed. As they provide a quantitative evaluation of the effect of each parameter both classifications are very useful to compare results obtained from tests performed on foam generated using different commercial foaming agents, different generation parameters (i.e. *Cf*, *FER*), and different foam generation systems (i.e. geometry of the foam lance, pressure or flow ratio of air and liquid).

The proposed classifications are based on a sizeable body of results of half-life tests. These tests were performed on many of the commercial foaming agents available, using *Cf* values suggested by each supplier and *FER* values in the range commonly adopted in TBM-EPB applications.

A detailed description is provided of the laboratory apparatuses used, with particular reference to the foam generation system. The standard test procedures are also reported. The experimental results are illustrated and the influence of several relevant parameters on half-life time, such as the concentration factor and the foam expansion ratio, are discussed. An accurate empirical correlation that describes the relationship between *hlt*, *Cf* and *FER* is proposed.

2. Foaming agents, laboratory foam generation, test apparatus and standard procedure

The soil conditioning process, during mechanized tunnelling, is performed by injecting foam to the front-face during excavation. Commercial chemical products usually used as foaming agents consist of solutions of water, surfactants and other additives, such as preservatives. The exact composition of the chemicals in unknown even though several studies have reported that Sodium Lauril Ether Sulphate (SLES) is constantly present. The present study involves the use of all the major foaming agents used and listed them progressively from A to O.

As specified in EFNARC standards, the quality and reproducibility of tests results are strongly reliant on the modality of generation of the foam used for the tests. In poorly produced foam the bubbles combine and break more rapidly. On the other hand, the foam produced with a laboratory foam generation system similar to those installed inside a TBM, ensures that the quality of the foam will be the same each time and, moreover, will be the same as that used during excavation.

The foam used in this study was generated using a laboratory foam generation system specifically designed and available at the Department of Structural and Geotechnical Engineering, Sapienza University of Rome. A diagram of the laboratory foam generation system used is shown in Fig. 1. This consists of four main lines with their respective links, the measurement system and control point of flow and pressure. The lines converge into two main injection points in the generation lance, a metallic cylinder filled with elements required to create turbulence and to progressively reduce bubble size. Several different filling elements (glass spheres, rivets, metal brushes, filters) were used. The results shown only refer to the foam lance arranged with a series of filter discs disposed in parallel, as represented in Fig. 1. This type of lance is one of the most efficient TBM foam lances.

Water and air pressure, as well as the flow of water, air and the foaming agent can be regulated by pressure gauges and flow meters on

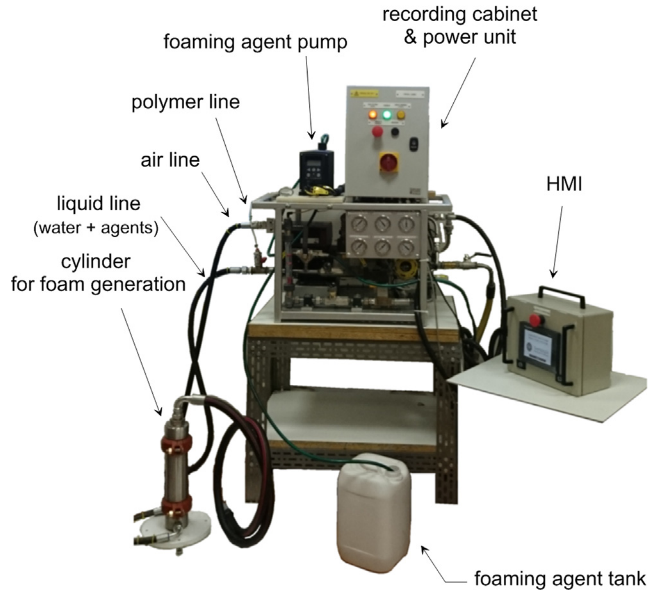


Fig. 2. Main components of the laboratory foam generation system.

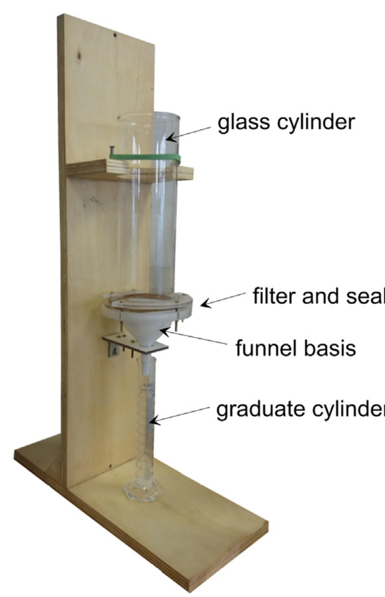
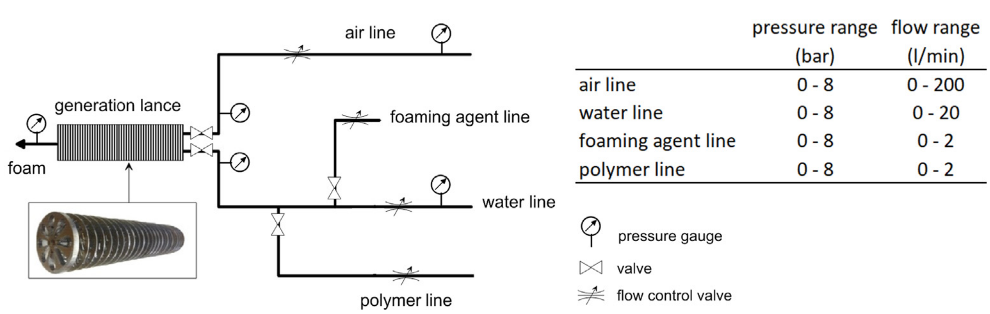


Fig. 3. Half-life test laboratory apparatus.



	pressure range (bar)	flow range (l/min)
air line	0 - 8	0 - 200
water line	0 - 8	0 - 20
foaming agent line	0 - 8	0 - 2
polymer line	0 - 8	0 - 2

Fig. 1. Laboratory foam generation system.

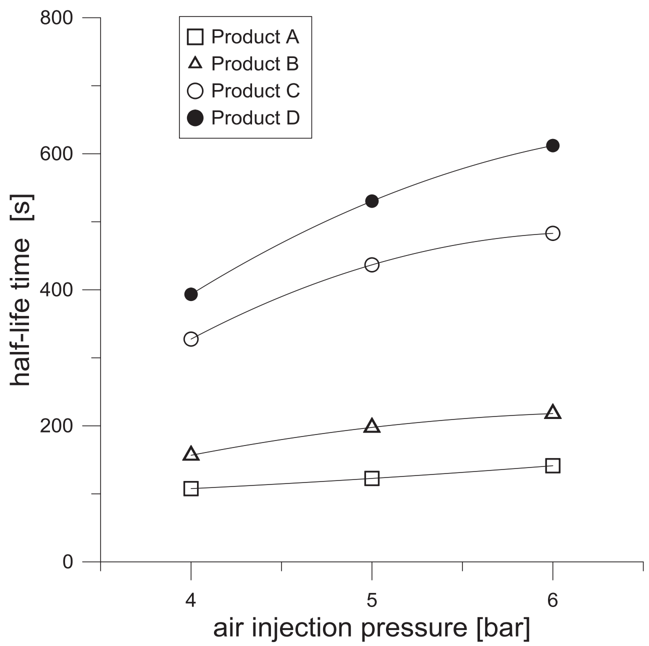


Fig. 4. Average values of *hlt* for $Cf = 2.5\%$ and $FER = 12$, as a function of injection pressure.

the machine and their values can be changed in real time during foam generation. All these parameters are controlled and monitored through the HMI (Human Machine Interface) unit (Fig. 2).

Properties of the foam generated are described by selected parameters:

$$Cf\,(\%) = \frac{m_{fag}}{m_{sol}} \cdot 100 \tag{1}$$

$$FER = \frac{V_f}{V_{sol}} \tag{2}$$

where Cf is the concentration factor, FER is the Foaming Expansion Ratio, m_{fag} is the mass of foaming agent used and m_{sol} is the mass of foaming solution, V_f is the volume of generated foam or injected foam and V_{sol} is the volume of the foaming solution.

As proposed by EFNARC (EFNARC, 2005), the half-life time of a foam is defined as the time required by a foam to drain 50% of the weight of the initial conditioning liquid used in foam generation. The test apparatus consists of a cylinder with a lower funnel and a graduate cylinder to collect the liquid drained from the foam (Fig. 3). According to the test procedure, a foam is prepared to the required FER, then the filter-funnel cylinder is filled with 80 g of the foam and, finally, the volume of liquid collected in the lower cylinder is measured to pinpoint the time required to collect 50% of the liquid used to generate the foam.

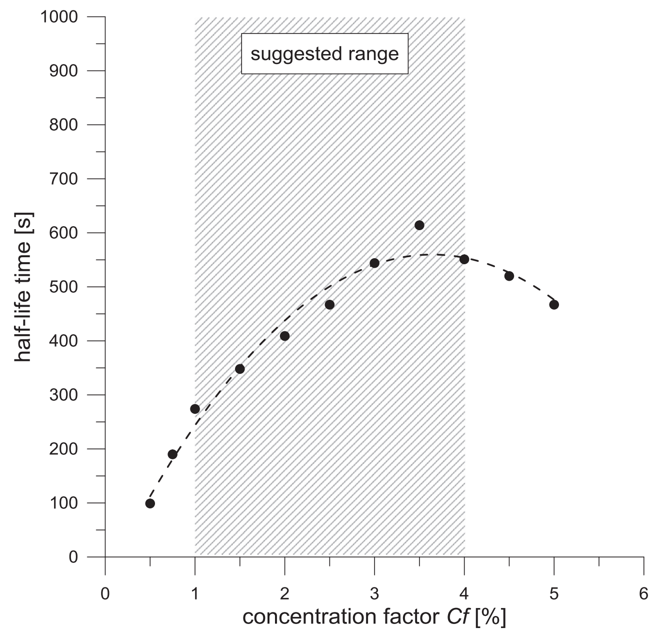


Fig. 6. Typical evolution of the half-life time with *Cf* measured for Product C.

As specified, the proposed standard foresees the use of an industrial plant of the type represented in Figs. 1 and 2 to generate foam in an environment with controlled pressure values (1 atm) and temperature (22°). For the value of the air injection pressure, the range usually employed in practical applications is 4–6 bar. We decided to use the value of 6 bar because it is related to a more stable generated foam, as can be seen in Fig. 4, where the results of half-life tests obtained on foam generated using different pressure value and four different products are reported.

Half-life tests were performed on foam generated using 15 different foaming agents provided by 7 of the largest suppliers, labelled from *A* to *O*, at *FER* values in the 8–18 range. Regarding *Cf* the adopted values were in the 0.75–2.5% range, according to the instructions on each

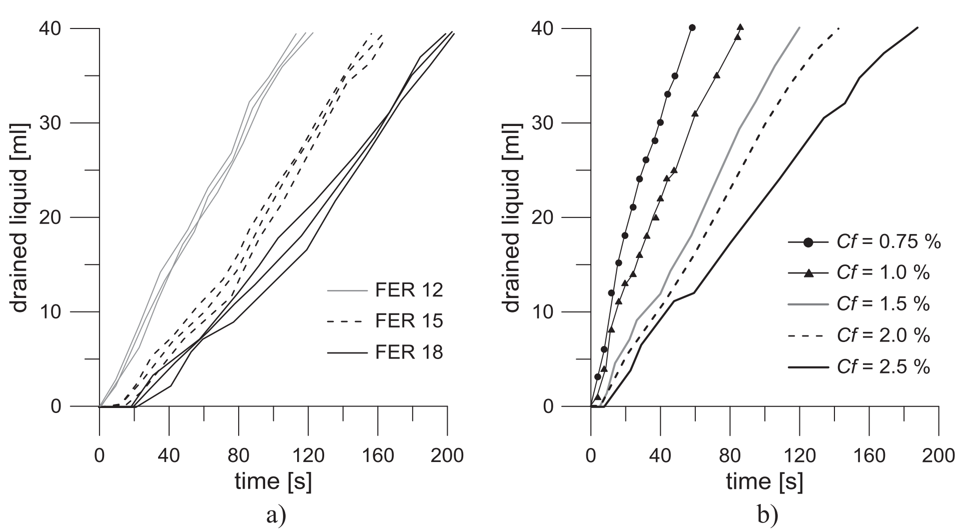


Fig. 5. Typical results of half-life tests: (a) effect of *FER* for a foam generated using Product B with $Cf = 2.5\%$ and (b) effect of *Cf* for a foam generated using Product C with $FER = 12$.

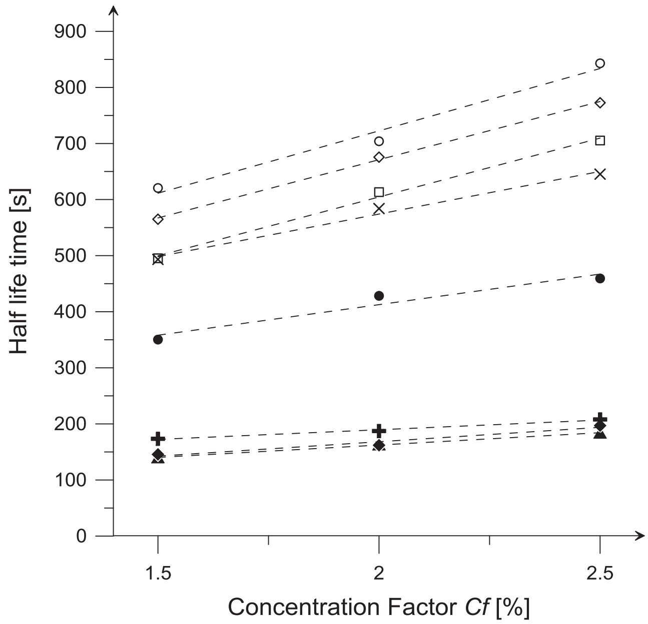


Fig. 7. Average values of *hlt* as a function of *Cf* (commonly used ranges) for Products G to M.

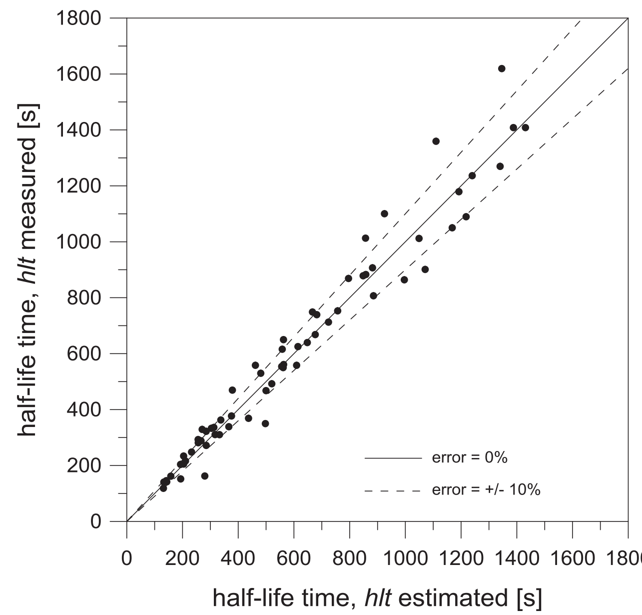


Fig. 9. Comparison between measured and estimated *hlt* values for all the tested products.

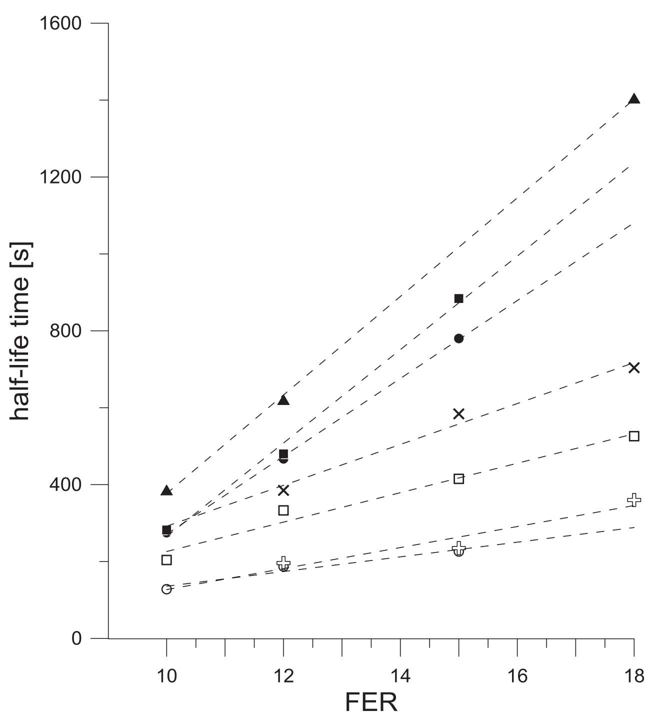


Fig. 8. Average values of *hlt* as a function of *FER* (range of values commonly used) for Products from G to M.

Table 1
Foam stability classification based on *hlt*.

Half-life time, *hlt* (s)	Foam stability category
0–150	Low
15–400	Moderate
400/750	Considerable
750–1200	High
> 1200	Very high

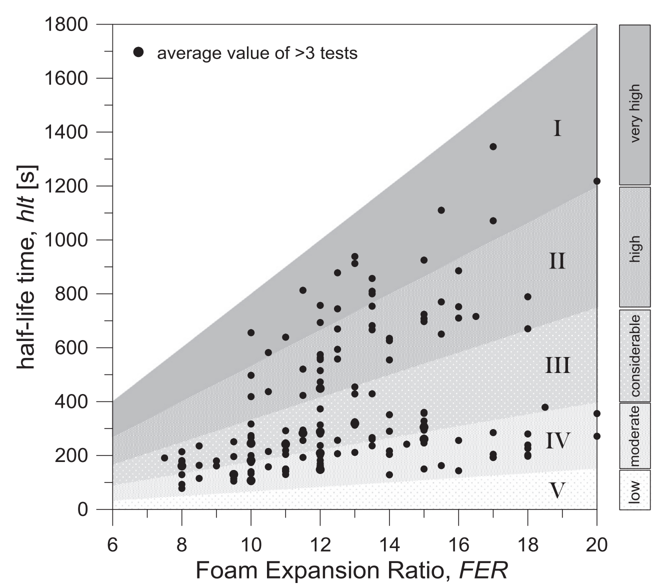


Fig. 10. Foaming product classification based on the stability of the generated foam.

technical datasheet.

3. Results and discussion

Preliminary experiments were performed to verify the repeatability of the test results obtained following the adopted standard procedure. All the following evaluations and graphics are based on average *hlt* values obtained performing more than 5 tests, with dispersion always within the range of ± 5% of the average values. Selected results are reported in Fig. 5 for 2 different products and different *Cf* and *FER* values. For all tested products, the foam stability increases as *Cf* and *FER* increase; several tests at *Cf* values of 1.5, 2.0 and 2.5% and at *FER* values of 12, 15 and 18 were performed and presented to show the good reproducibility of the obtained results.

The data reported in Fig. 6 show that a linear trend well approximates the results obtained for *Cf* vales between 1% and 3%. As expected, below that range, the stability of the foam tends to decay very rapidly as do the corresponding *hlt* values. Above a certain surfactant concentration, the critical micelle concentration value, the surfactant monomers tend to form aggregates that generate stable bubbles in the air-water medium (Wang et al., 2017). Over the same range, further increases in *Cf* lead to a reduction of *hlt*. This is probably due to the presence of too many micelles that may cause increased collision among these structures, leading to a reduction in the foam stability.

In Fig. 7 the results of a series of half-life tests performed on different products for commonly used *Cf* values (1.5–2.5%) are reported for the foaming agents "G" to "M". Each point represents the average value obtained in three tests, with dispersion within ± 5% range of the average values. It is clear that *hlt* approximately linearly increases as *Cf* increases. The increase of the gradient of this linear relation with the increase of the stability of the foam (*hlt/Cf*) is also obvious. Moving from the least stable to the most stable foam, this gradient changes from under 40 s to above 200 s. This trend is valid for all the products tested and for all values of foam generation parameters used.

Eq. (3) expresses the value of *hlt* as a function of *Cf*, taking as a reference the *hlt* value obtained using $Cf = 2.0\%$ ($hlt_{(Cf=2\%)}$) and assuming a linear interpolation of the experimental results:

$$hlt_{(Cf)} = hlt_{(Cf=2.0\%)}[1 + 0.3(Cf - 2.0)] \tag{3}$$

Similar to the relation between *Cf* and *hlt* shown in Fig. 7, Fig. 8 shows the relation between *FER* and *hlt*. It is clear that *hlt* has a wide range of variation and that the influence of *FER* is more marked if compared with that of *Cf*. In fact, by doubling *Cf* from 1% to 2% it is possible to increase *hlt* by about 250 s at most, while by varying the *FER* from 10 to 18 it is possible to increase *hlt* by about 1000 s.

The half-life time increases linearly as the *FER* increases and also the *hlt/FER* ratio increases as the stability of the foam increases, varying from a value of 10 s to more than 100 s. The correlation between *hlt* and *FER*, based on a linear interpolation, can be mathematically expressed by the following equation (4):

$$hlt_{(FER)} = hlt_{(12)} + (0.254{\cdot}hlt_{(12)} - 15)(FER - 12) \tag{4}$$

where $hlt_{(12)}$ is the value of *hlt* obtained by using a reference *FER* of 12.

Combining Eqs. (3) and (4), and assuming as standard reference the parameter hlt^*, the value of *hlt* of a foam generated by employing a product with $Cf = 2.0\%$ and having a *FER* of 12, $hlt^* = hlt_{(FER=12,\ Cf=2.0\%)}$, we obtain the following general empirical correlation:

$$hlt = [hlt^* + (0.254{\cdot}hlt^* - 15)(FER - 12)][1 + 0.3(Cf - 2)] \tag{5}$$

The previous correlation is highly accurate. The *hlt* values experimentally obtained coincide with the corresponding values obtained with Eq. (5) (Fig. 9); the differences between measured and estimated values are generally under 10%.

4. Proposed classifications

Based on the test results obtained for 15 commercial foaming agents, using different *Cf* and *FER* values, the following classification system (Table 1) is proposed. According to this classification, foam stability falls under 5 categories defined as low for $htl < 150$ s and very high for $hlt > 1200$ s; other intermediate categories are moderate (150–400 s), considerable (400–750 s) and high (750–1200 s).

The foaming agents can be classified according to their ability to generate a stable foam. As described in the previous section, for each product (chemical composition and concentration) the value of *hlt* changes considerably by varying the *FER*. Hence, even when using the same foaming agent, it is possible to generate foams that fall under different foam stability categories. Therefore, when classifying the products, the *FER* should be taken in account since this affects the stability of the foam irrespective of the agent used. Fig. 10 reports the results of the tests performed and identifies five classes. Products that generate foam with *hlt* values at the bottom of the graph (Fig. 10), are classified as class V. Class V products only generate low stability foam. Class I products, at the opposite end of the scale, can generate very stable foam with *hlt* over 1600 s.

With the development of new products or more effective foam generators for tunnelling applications, the classification should be modified in the future by expanding the higher class and category or by introducing further classes and categories.

5. Conclusions and developments

Foaming agents are currently used in tunnelling with TBM-EPB to condition the excavated soil. Conditioned soil becomes a homogeneous soft paste with a number of well-known advantages. The consistency of the conditioned soil should be stable during its permanence inside the excavation chamber to maintain these benefits. The first step in studying changes in the properties of conditioned soil over time is to investigate the stability of the foam itself.

Here, foam stability was studied carrying out a large number of half-life tests on 15 commercial products, in standard conditions of temperature, pressure in the environment and generation pressure, employing a modern and effective foam generation system. The main results are summarized below.

- Experimental results confirm the well-known relation between the stability of the foam and *Cf* and *FER* and, moreover, provided empirical correlations that describe the evolution of the *hlt* of the foam with the variation of the generation parameters (Eq. (5)).
- A foam classification was proposed, based on its stability. Based on *hlt* values, 5 categories of foam stability have been defined.
- A classification of each agent based on their ability to generate stable foam, is also proposed: the products are divided into 5 classes, ranging from Class I to V.
- The proposed classification of products is useful for commercial producers to assess the quality of their products and improve their performance.
- Both the proposed classifications are useful for engineers and constructors to select the most suitable product for their scope (cost versus benefit analysis for tunnelling using TBM equipped with EPB technology) in the design and construction phases, with only a few laboratory tests needed.

The next step of our current research is the study of foam stability under cyclic variations of pressure and the stability of treated soil using different soils and foams with different half-life times.

References

Adoko, A.C., Gokceoglu, C., Yagiz, S., 2017. Bayesian prediction of TBM penetration rate in rock mass. Eng. Geol. 226, 245–256. https://doi.org/10.1016/J.ENGGEO.2017.06.014.

Anagnostou, G., Kovári, K., 1996. Face stability conditions with earth-pressure-balanced shields. Tunn. Undergr. Sp. Technol. 11, 165–173. https://doi.org/10.1016/0886-7798(96)00017-X.

EFNARC, 2005. Specification and guidelines for the use of specialist products for Mechanized Tunnelling (TBM) in Soft Ground and Hard Rock, Recommendation of European Federation of Producers and Contractors of Specialist Products for Structures.

Gong, Q.M., Yin, L.J., Wu, S.Y., Zhao, J., Ting, Y., 2012. Rock burst and slabbing failure and its influence on TBM excavation at headrace tunnels in Jinping II hydropower station. Eng. Geol. 124, 98–108. https://doi.org/10.1016/J.ENGGEO.2011.10.007.

Liu, X.X., Shen, S.L., Zhou, A., Xu, Y.S., 2019. Evaluation of foam conditioning effect on groundwater inflow at tunnel cutting face. Int. J. Numer. Anal. Meth. Geomech. 43 (2), 463–481.

Merritt, A.S., 2004. Conditioning of Clay Soils for Tunnelling Machine Screw Conveyor. PhD Thesis. University of Cambridge.

Milligan, G., 2000. Lubrication and soil conditioning in tunnelling, pipe jecking and microtunnelling: a state of the art review.

Miliziano, S., de Lillis, A., 2019. Predicted and observed settlements induced by the mecha-nized tunnel excavation of metro line C near S. Giovanni station in Rome. Tunnell. Undergr. Space Technol. 86, 236–246.

Mori, L., Mooney, M., Cha, M., 2018. Characterizing the influence of stress on foam conditioned sand for EPB tunnelling. Tunn. Undergr. Space Technol. 71, 454–465.

Repetto, L., Fidelibus, C., 2017. Decision plots for preliminary design of single-shield TBMs. Eng. Geol. 216, 134–139. https://doi.org/10.1016/J.ENGGEO.2016.11.023.
Shen, S.L., Wu, H.N., Cui, Y.J., Yin, Z.Y., 2014. Long-term settlement behaviour of metro tunnels in the soft deposits of Shanghai. Tunn. Undergr. Space Technol. 40, 309–323.
Thewes, M., Budach, C., 2010. Soil conditioning with foam during EPB tunnelling. Geomech. Tunn. 3, 256–267. https://doi.org/10.1002/geot.201000023.
Thewes, M, Budach, C, Bezuijen, A, 2012. Foam conditioning in EPB tunnelling. In: Viggiani, Giulia (Ed.), Geotechnical Aspects of Underground Construction in Soft Ground. CRC Press, pp. 127–135. https://doi.org/10.1201/b12748-19.
Tokgöz, N., Serkan Binen, I., Avunduk, E., 2015. An evaluation of fine grained sedimentary materials in terms of geotechnical parameters which define and control excavation performance of EPB TBM's. Tunn. Undergr. Sp. Technol. 47, 211–221. https://doi.org/10.1016/J.TUST.2014.12.007.
Vilardi, G., Sebastiani, D., Miliziano, S., Verdone, N., Di Palma, L., 2018. Heterogeneous nZVI-induced Fenton oxidation process to enhance biodegradability of excavation by-products. Chem. Eng. J. 335, 309–320. https://doi.org/10.1016/j.cej.2017.10.152.
Wang, H., Li, J., Wang, Z., Wang, D., Zhan, H., 2017. Experimental investigation of the mechanism of foaming agent concentration affecting foam stability. J. Surfactants Deterg. 20, 1443–1451. https://doi.org/10.1007/s11743-017-2004-2.
Wu, Y., Mooney, M.A., Cha, M., 2018. An experimental examination of foam stability under pressure for EPB TBM tunneling. Tunn. Undergr. Sp. Technol. 77, 80–93. https://doi.org/10.1016/J.TUST.2018.02.011.