Proposed Methodology for Clogging Evaluation in EPB Machines

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ABSTRACT

Clogging occurrence has long been an issue for EPB drives, through not only pure clay soils, but also in mixed soils with sufficient clay content for clogging to happen. It occurs when clay particles adhere to metal surfaces of excavation tools because of the attractive forces of the clay particles and the presence of water between the clay-metal surface. The occurrence of clogging in Earth Pressure Balance Machines (EPBMs) leads to several issues such as high torque requirements of the machine, drastic performance reductions and lowering of the advance rates, resulting in long and frequent interventions for cleaning of the clogged tools, adding costs to the excavation.

While evaluation methods of clogging occurrence have been already proposed by several authors, there is still a lack of a standardised method suitable for evaluating not only the clogging potential of any soil, including mixed sandy clay soils, but also potential gains from soil conditioning in order to diminish these challenges by means of foam and/or polymer addition to the excavation face. There is a need in the tunnel industry for a method that would provide reliable information on the clogging potential, in addition to being simple, fast and of low cost, which could be easily reproduced by any soil laboratory, or even on the project site.

The methodology here presented is a combination of two simple devices. The first one, already proposed as a clogging evaluation methodology, involves a Hobart mixer and a B-flat beater used to define an empirical stickiness evaluation parameter (λ). After an extended test campaign with pure clays and mixed clay sand soils, it was clear that only the Hobart methodology was not enough to provide reliable information about the real tendency of a certain soil to clog in a tunnel drive. A new additional device was then implemented, which adds to the Hobart method a kinetic energy, by dropping the B-flat beater from a certain height, balancing the forces between the stress adhesion and the kinetic energy, which in turn represents the movement of the machine cutterhead. This combination of methods could provide a reasonable approximation of the potential for clogging to happen along EPB tunnel drives.

This paper presents preliminary results of this new proposed combined methodology for clogging evaluation, as well as the evolution of the research and testing campaigns which lead logically to the addition of the beater dropping stage. It also mentions the future work that should be continued to achieve a better calibration of this methodology with real tunnel drives and, by adding more data, empirically refining precise ranges of low, medium and high clogging potential.

Key Words: Clogging, Earth Pressure Balance Machine, Soil Conditioning, Mixed Ground

1. INTRODUCTION

Clogging issues have been investigated for over a century, starting with a correlation between the changes of the soil state, depending on its water content and its plasticity, defined by Atterberg (1911), due to the problems with clogging in the agriculture tools. Later, in the field of soil mechanics, this same soil properties were correlated with mechanical soil behavior by Terzaghi (1926). Casagrande (1932) defined ways to measure these changes in the soil state originating the liquid and plastic limits methodologies, which are still applied today.

Several decades later, with the evolution of the tunnelling field and the development of the Earth Pressure Balance Machines (EPB), issues with clogging along fine-grained soils brought a new challenge. Several authors investigated and described the problems related to the occurrence of clogging during EPB tunnel drives, describing its main problems, such as high torque requirements of the machine, extreme performance reductions and decrease in the advance rates, leading into long and frequent interventions and additional costs (Thewes 1999, 2004; Feinendegen et al. 2011; Zumsteg and Puzrin 2012; Hollman and Thewes 2012, 2013; Hollman, Thewes and Weh 2014; Thewes and Hollman 2014, 2016; Peila et al. 2016; and others).

Two different approaches are available in terms of estimating the clogging potential. An indirect one, taking into consideration soil properties, is the clogging potential graph proposed by Hollman and Thewes (2012). This graph considers the plastic and liquid limit of the soil, the changes in the water content and the consistency index (Ic), correlating that with distinct ranges of clogging potential, from absent (lumps or fines dispersing) to strong clogging. For the design of this graph, data from several projects with clogging occurrence were compiled, therefore, making it relevant to tunnel drives.

The second approach, which so far does not have any standardization, is a more direct one, which focus in directly measuring the clogging potential with laboratory devices. One of these methods was proposed by Zumsteg and Puzrin (2012), using a HOBART mixer. This mixer is available worldwide and is used not only for laboratory tests, but also for the bakery industry. According to the above-mentioned authors, by simply mixing in the machine a certain amount of the soil, with a B-flat beater, and measuring the amount of the soil that gets stuck in the beater, would be possible to obtain an empirical stickiness evaluation parameter (λ), related to the clogging potential.

After an extended testing campaign, Oliveira et al. (2017) concluded that this method was not enough to define the clogging potential for EPB drives and that an extra stage should be added to this first HOBART mixing methodology. The discrepancies between what could be expected as a real clogging occurrence, especially concerning the plasticity of the samples, and the results obtained with the original HOBART testing methodology, were even larger in the case of mixed clay sand soils. It must be considered that there is significant kinetic energy at the tool-soil interface in front of the cutterhead and even inside the excavation chamber, so the correlation between real clogging and an index based on the B-flat beater with soil stuck on it without the addition of kinetic energy, should not really be expected. The challenge, though, was to define the amount of this kinetic energy that should be applied. Consequently, a correlation between the clogging potential obtained with a new combined methodology and the graph from Hollman and Thewes (2012) was done, obtaining more suitable results, as presented ahead.

2. CLOGGING EVALUATION WITH THE HOBART MIXER

Zumsteg and Puzrin (2012) described their method for empirically estimating the clogging potential of soils by using a HOBART mixer and a B-flat beater. Initially, the machine used had a 20-liter capacity and, later, it was changed to a smaller machine with 5-liter capacity (Zumsteg, Puzrin and Anagnostou 2016), illustrated here in Figure 1. The proposed methodology is quite simple, consisting of initially measuring the total weight of the soil, mixing it for three minutes with the speed 1 (around 100 rpm), and, afterwards, measuring the weight of the soil that remained stuck in the beater, obtaining the parameter λ. This empirical stickiness parameter (λ) is the ratio of the weight of the soil stuck in the beater over the weight of the entire sample (Equation 1). Depending on the λ value obtained, the tested sample can be classified as low (λ < 0.2), medium (λ between 0.2 and 0.4) or high (λ > 0.4) clogging potential, according to Zumsteg, Plötze, and Puzrin (2013).

$$\lambda = G_{MT}/G_{TOT} \qquad (2)$$

Figure 1. HOBART machine (left) and the B-flat beater (right) used to estimate the clogging potential.

Following the HOBART testing methodology, as proposed by Zumsteg and Puzrin (2012), a total of 35 samples was tested in a preliminary testing phase. These samples had different proportions of clay and sand, for two different clay minerals; bentonite (cited here as B) and kaolinite (cited as K). Details of all the tested samples and methodology can be consulted in Oliveira et al. (2017).

After several tests, especially for low plasticity samples with a relevant sand contribution, most of the soil stuck in the beater would be easily removed with any vibration or impact of the mixing tool. Likewise, for a certain consistency range and soil combinations, most of the soil would still remain stuck, even after the beater was abruptly jolted. Figure 2 illustrates four different cases for two different clay mineral samples. On the top left is the example of a sample with 30% of kaolinite mixed with fine sand, and on the top right, a mixture of 20% of bentonite with fine sand, both in the consistency index of zero. In this case, without any impact of the beater, the sample would be classified as high clogging (λ=0,9, and λ=1,0, respectively for kaolinite and bentonite samples). However, after dropping the sample always from the same height, once (λ_1), twice (λ_2), or even three times (λ_3), there was a significant decrease of the soil stuck in the beater, leading into non-existent clogging. Nevertheless, for lower consistencies, as seen at the bottom of the figure, there was a significant amount of soil in the beater, even after several jolting's of the mixing tool.

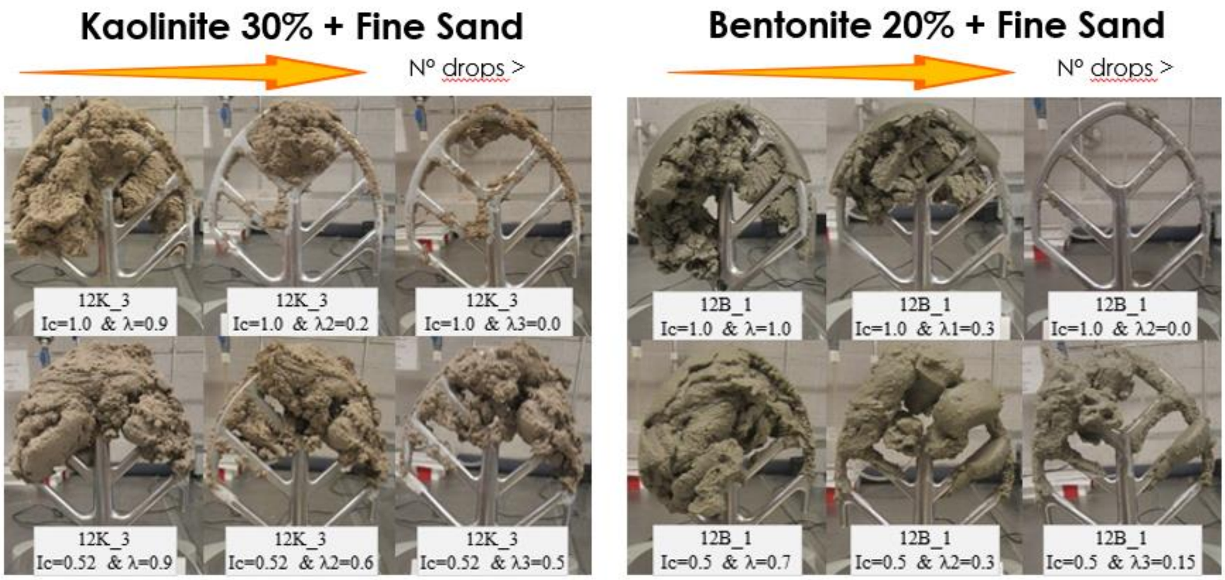

Figure 2. Two tested samples, with two distinct consistencies (Ic), on the left a kaolinite mixture and on the right, a bentonite one. The yellow arrow indicates the direction which increases the number of drops of the beater, providing different values for λ (λ = zero drop; λ1 = one drop and so on).

Figure 3 presents all the samples plotted in the Hollman and Thewes (2012) graph. On the top graph the samples have not received any dynamic jolting, and, on the bottom are plotted the results after three drops of the beater, from the same height. There is a better fitting between the graphed clogging potential ranges and the empirical parameter λ_3, using three drops of the beater, compared to the sampling of stuck soil without applying any kinetic energy (λ). However, too many discrepancies can be detected and, certainly, the lack of a solid procedure for dropping the beater could be influencing the results.

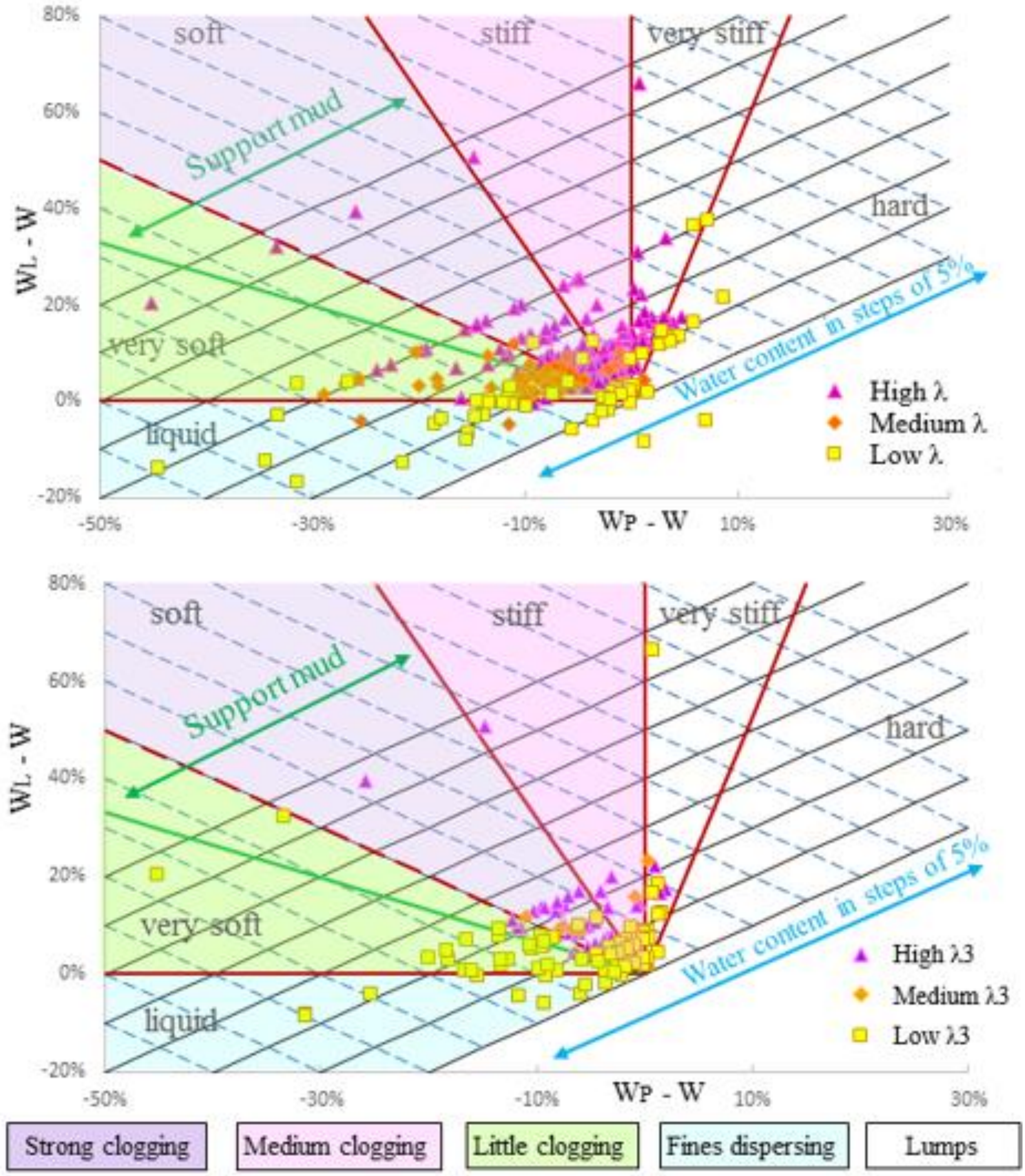

Figure 3. Results from preliminary testing phase plotted in the clogging potential universal graph (modified from Hollman and Thewes 2012). The top chart represents the samples without any drop of the beater, as originally defined by Zumsteg and Puzrin (2012) and the bottom chart presents the modified version, after three drops of the beater.

3. NEW TESTING DEVICE AND MODIFIED METHODOLOGY

Designed to provide the B-flat beater a free fall from always the same height (37,5 cm) and along the same axis, a new testing device was assembled and tested with several samples, in combination with the HOBART mixer methodology. Figure 4 illustrates this new assembled device, denominated A.T.U.R., which stands for *Adhäsive Tone Untersuchung RUB-Queens* (RUB-Queens Clay Adhesion Tool), from a research cooperation between Queen's University, in Canada, and Ruhr Universität Bochum, in Germany.

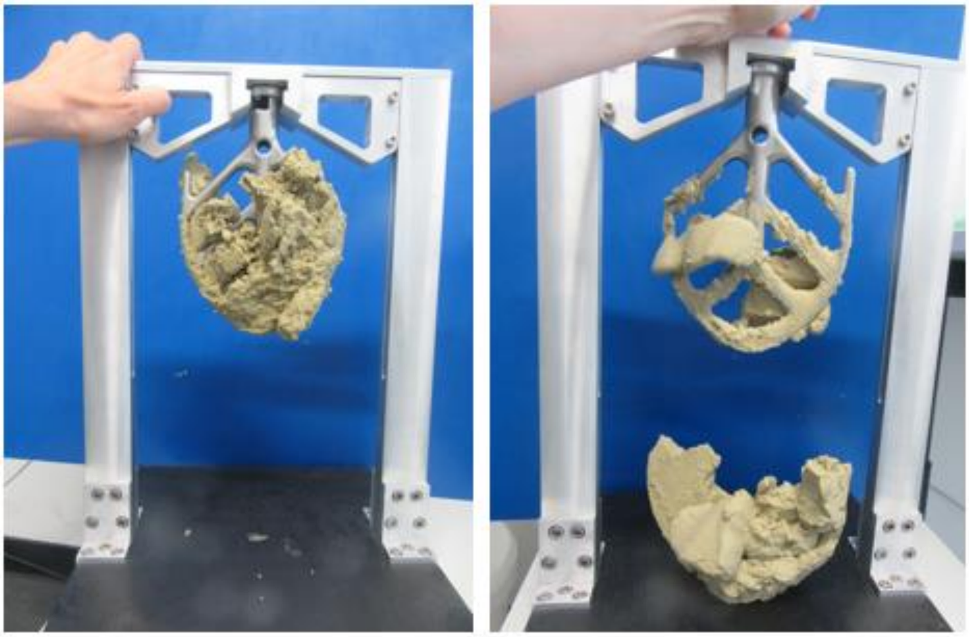

Figure 4. A.T.U.R. device designed to add a free fall drop to the beater with the soil stuck on it, after the first stage of mixing the soil with the HOBART machine. On the left, the beater before the drop and on the right, after the first drop, showing the partial release of the material.

Figure 5 presents a simplified schematic explanation for dropping the beater. A certain material with clay content, at a certain consistency index, for example, Ic = 0, would have a certain adhesion stress "holding" the sample towards the metal surface on which is clogged to, along a certain surface area (top of the figure). At a lower Ic, the area of this adhesion stress surface is bigger, which, depending on the soil sample, could lead into a higher adhesion stress. As to say, whenever clogging is pronounced, the counterbalance of a kinetic energy (red arrow) would not be enough to detach the sample from the surface. Ideally, this counter balance kinetic energy should be calibrated with a high amount of tunnel data, and, undoubtedly, that could increase the refinement of this calibration.

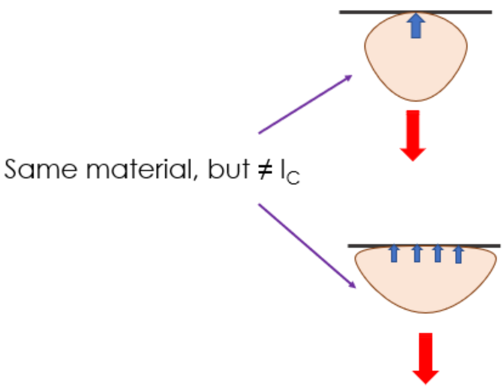

Figure 5. Simplified scheme of the drop stage added to the HOBART mixing methodology.

4. INITIAL CALIBRATION AND RESULTS

A testing campaign was initiated after the assemblage of the new testing device, A.T.U.R., and some of the preliminary results are here presented. Initially, the tests were conducted with a sample of 20% of bentonite and fine sand, however, when crossing the obtained results with the chart from Hollman and Thewes (2012), it was noticed that even for a higher plasticity index (IP = 59) all the results, with or without dropping the beater, would imply in significantly less clogging than the samples with higher kaolinite content, but significantly lower plasticity index (e.g. Kaolinite 50% with IP = 12).

The Hollman and Thewes (2012) graph was based mainly on pure clay samples, from sedimentary origin (higher grain selection when compared to a tropical residual ground, for example), and would not necessarily be applicable to samples with low clay content and a significant sand contribution, a mixed clay sand soil. Most probably it would be necessary to include a new parameter, the friction of the sand grains, for example, which its influence is still not yet clearly understood in the clogging potential. Therefore, it was decided to start the calibration of the kinetic energy applied within the new device, A.T.U.R., with pure kaolinite samples. It was considered to use, as testing points, the consistency index values just above and below the clogging potential boundaries, as defined by the graph from Hollman and Thewes (2012), indicated here in the Figure 6.

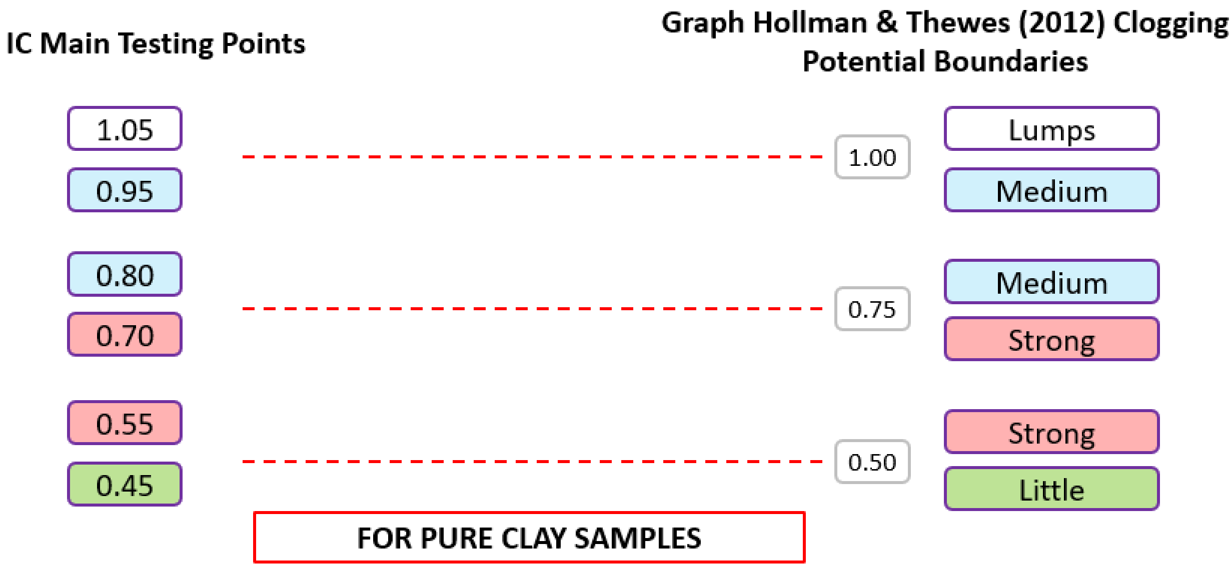

Figure 6. Main testing points for the initial calibration of A.T.U.R., considering the clogging potential boundaries as defined by Hollman and Thewes (2012) chart.

Figure 7 illustrates the dropping sequence, from left to right. Initially, the sample was weighted, after mixing with the HOBART machine, obtaining λ_0 (0 indicates no drop), then the beater was placed in the A.T.U.R., released, and weighted again, acquiring λ_1, and continually repeating until λ_3. The first results indicated that even three drops were not enough to obtain a good fit with the clogging potential graph, most probably because the stiffness of the base used for the preliminary stage was higher than the one assembled for A.T.U.R. Accordingly, the last tests included a final stage with seven drops, obtaining λ_7.

Figure 8 presents the results for three different samples with kaolinite and fine sand. All the samples were built in the laboratory to ensure reproducibility, allowing the adjustment of only desired parameters (e.g. clay fraction). From these three graphs (30, 50 and 70% of kaolinite) it is possible to observe that at higher ($Ic > 0.75$) and lower ($Ic < 0.4$) consistencies, the differences between λ_0 and λ_3 are greater, exactly because clogging should not be expected at these consistencies. This shows that the empirical stickiness parameter λ_0 does not reflect what is expected as clogging potential.

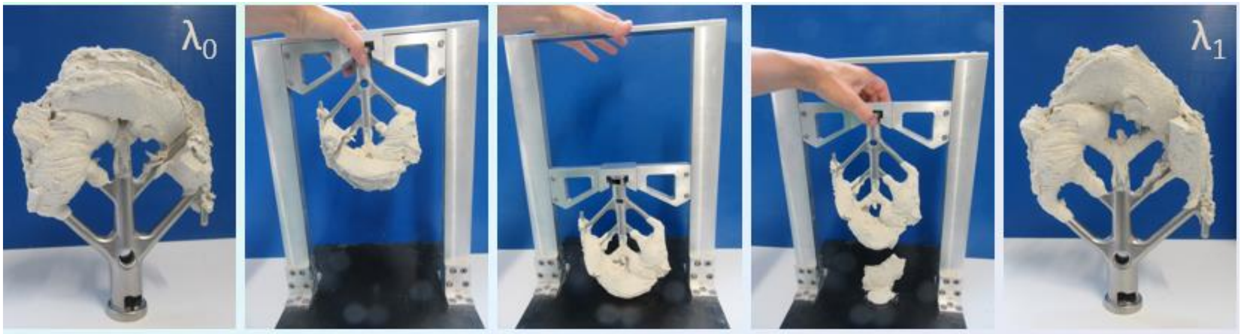

Figure 7. Sequence of the stage after the HOBART mixer, from left to right, no drop (λ_0) and dropping the beater and obtaining (λ_1).

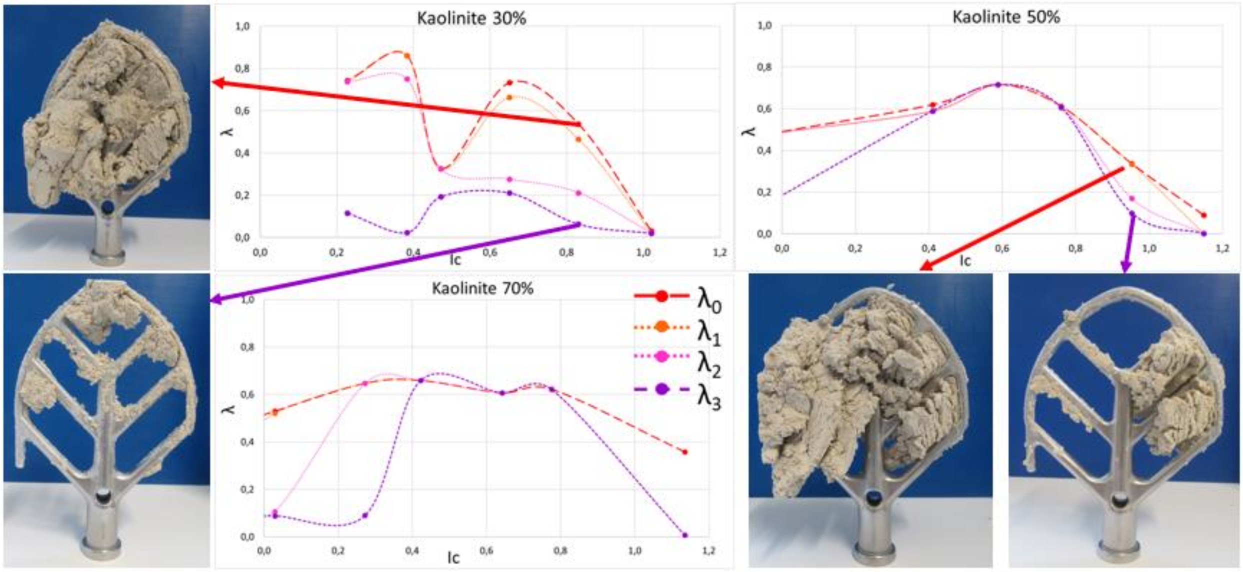

Figure 8. Results from three different samples, containing 30, 50 and 70% of kaolinite, showing 4 different empirical stickiness values of λ.

Table 1 presents the calibration for the combined methodology of the HOBART machine with the dropping device, A.T.U.R., done for pure kaolinite samples. The results were compared to the limits of clogging potential define by Hollman and Thewes (2012), which, as already mentioned, were based on real tunnel drives. To help the visualization, the cells were colored according to the clogging potential (yellow – low; orange – medium; red – high). Also, the limits defined for these ranges have been adjusted to better fit the ranges from Hollman and Thewes (2012) graph, with λ_x values (x representing any number of drops, including none): < 0,2 = low clogging potential; between 0,20 and 0,46 = medium clogging potential and higher than 0,46 = high clogging potential. Certainly, these values need to be adjusted with more data obtained and crossed with tunnel drives.

Without any drop of the beater, represented by the column λ_0, would imply in high clogging for all the consistency indexes, and the values obtained for $\lambda_{7,}$ would have a better fit with the ranges for the potential of clogging as defined by Hollman and Thewes (2012), very likely being a better fit than the HOBART methodology as the original proposed. There are still values of λ_7 (marked in bold and italic on the table) that does not entirely fit with the Hollman and Thewes (2012) chart, nonetheless the results should be closer to the reality of clogging occurrence in EPB machines than the original empirical stickiness evaluation with solely the HOBART machine.

Table 1. Results for the initial calibration of HOBART + A.T.U.R values compared with Hollman and Thewes (2012) clogging potential ranges (showed as H&T in the table).

TEST ID	TEST N°	W	IC	λ0	λ1	λ2	λ3	λ7	H&T
Kpure_T2	1	40,5	1,0	0,62	0,62	0,62	0,62	0,06	Lumps
	2	42,2	0,9	0,65	0,65	0,65	0,39	0,39	Medium
	3	47,2	0,7	0,60	0,60	0,60	0,60	0,60	Strong
	4	49,8	0,6	0,56	0,56	0,56	0,56	0,56	Strong
	5	54,1	0,4	0,64	0,64	0,64	0,29	0,09	Little
	6	56,8	0,2	0,54	0,54	0,53	0,30	0,13	Little
Kpure_T3	1	40,2	1,0	0,62	0,62	0,62	0,27	0,08	Lumps
	2	42,4	0,9	0,56	0,56	0,56	0,56	0,41	Medium
	3	45,9	0,7	0,67	0,67	0,53	0,53	0,48	Strong
	4	48,8	0,6	0,60	0,60	0,60	0,60	***0,37***	Strong
	5	51,8	0,5	0,64	0,64	0,64	0,64	0,64	Strong
	6	53,3	0,4	0,66	0,66	0,65	0,65	0,13	Little
Kpure_T4	1	39,8	1,0	0,63	0,62	0,61	0,58	0,07	Lumps
	2	41,5	0,9	0,59	0,59	0,59	0,59	***0,56***	Medium
	3	44,8	0,8	0,67	0,67	0,67	0,67	***0,62***	Medium
	4	47,1	0,7	0,66	0,66	0,66	0,66	0,66	Strong
	5	50,6	0,5	0,71	0,71	0,71	0,71	0,62	Strong
	6	53,5	0,4	0,61	0,61	0,61	0,60	0,10	Little
	7	61,6	0,0	0,53	0,52	0,16	0,12	0,06	Little
Kpure_T5	1	39,9	1,0	0,64	0,64	0,64	0,64	0,09	Lumps
	2	41,3	0,9	0,67	0,64	0,61	0,58	0,46	Medium
	3	45,1	0,8	0,60	0,60	0,60	0,60	***0,58***	Medium
	4	47,8	0,6	0,66	0,66	0,66	0,66	0,66	Strong
	5	50,9	0,5	0,72	0,72	0,72	0,72	***0,35***	Strong
	6	53,9	0,4	0,68	0,68	0,67	0,67	0,09	Little
	7	61,1	0,0	0,52	0,51	0,22	0,13	0,05	Little

5. CONCLUSIONS

It is essential to consider that clogging occurrence along EPB tunnel drives is a function of several variables. Those variables are not merely related to the properties of the soil and underground water, but as well as other factors, such as the machine specifications, the effect of higher atmospheric pressure and temperature, and, finally, the applied conditioning additives, especially the effect of foam and anti-clay polymers. Many times, an additive that might work perfectly in one site, might not work on another. This scenario brings into a trial-and-error approach, which many times could lead into a condition that might be too late to be modified before severe clogging is already happening, leading into tunnel drive issues and major delays.

It is also a difficult task, although not impossible, to combine all these variables into a holistic model and achieve a final solution. Ultimately, it must be considered that those machines excavate natural materials, and, quoting Terzaghi: “Unfortunately, soils are made by nature and not by man, and the products of nature are always complex… Its properties change from point to point while our knowledge of its properties is limited to those few spots at which the samples have been collected” (in Goodman 1998).

Therefore, it is necessary tools and methodologies which allow us to investigate clogging in any possible scenario, providing a probabilistic assessment of the clogging potential, as well as the effectiveness of certain conditioning agents, even before the tunnel is excavated, avoiding to solely rely on the trial-and-error approach, and planning ahead, certainly diminishing risks and costs of the project.

A simple, easy and, rather not expensive, methodology, which allows to assess and estimate clogging occurrence, and that could be easily duplicated in any soil laboratory, or even at the project site, generating more data to be compiled and compared, could, unquestionably, be of great benefit to the tunnel industry. This new proposed methodology, which combines the HOBART mixer with the dropping device A.T.U.R., does not intend to reproduce the total reality of EPB tunnel drives and clogging issues, as this might be an extremely complex task, however, it does bring us closer to the possibility of a good assessment of the clogging potential, foreseen great improvement with the increase of laboratory and on-site data.

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7. CITATIONS AND REFERENCES

Atterberg, A. (1911). Die Plastizität der tone. Int. Mitt. Bodenkunde, 1, pp. 10-43.

Casagrande, A. (1932). Research on the Atterberg limits of soils. Public Roads, 13, pp. 121-130.

Feinendegen, M., Ziegler, M., Weh, M., and Spagnoli, G. (2011). Clogging during EPB-tunnelling: Occurrence, classification and new manipulation methods. Presented at the ITA 2011 WTC, Helsinki, pp. 767-776.

Goodman, R.E. (1998). Karl Terzaghi – The engineer as Artist. ASCE Press, Virginia, 340 p.

Hollmann, F., and Thewes, M. (2012). Evaluation of the tendency of clogging and separation of fines on shield drives. Geomech. & Tunnelling 5, pp. 574-580.

Hollmann, F., and Thewes, M. (2013). Assessment method for clay clogging and disintegration of fines in mechanised tunnelling. Tunnelling and Underground Space Technology, Vol. 37, pp. 96-106, http://dx.doi.org/10.1016/j.tust.2013.03.010

Hollmann, F., Thewes, M., and Weh, M. (2014). Einflüsse von Verklebungen auf die Materialförderung von Schildvortrieben (Influence of Clogging on the Muck Transport in Shield Machines). Tunnel - International Journal for Subsurface Construction, No. 3, pp. 10-19.

Oliveira, D.G.G. de, Diederichs, M.S., Thewes, M. and Langmaack, L. (2017). EPB Tunneling Through Clay Sand Mixed Soils - Suitable Laboratory Tests. Submitted to the Geotechnical Testing Journal (submitted).

Peila, D., Picchio, A., Martinelli, and D. Dal Negro, E. (2016). Laboratory tests on soil conditioning of clayey soil. Acta Geotechnica 11, pp. 1061-1074, http://dx.doi.org/10.1007/s11440-015-0406-8

Terzaghi, K. (1926). Simplified Soil Tests for Subgrades and their Physical Significance. Public Roads, Vol. 7, No. 8, pp. 153–170.

Thewes, M. (1999). Adhäsion von Tonböden beim Tunnelvortrieb mit Flüssigkeitsschilden. PhD Thesis, Bericht aus Bodenmechanik und Grundbau, Bergische Universität Wuppertal, Fachbereich Bauingenieurwesen, p. 190.

Thewes, M. (2004). Schildvortrieb mit Flüssigkeits- oder Erddruckstützung in Bereichen mit gemischter Ortsbrust aus Fels und Lockergestein. Geotechnik 27, pp. 214-219.

Thewes, M., and Hollmann, F. (2014). TBM-specific testing scheme to assess the clogging tendency of rock (TBM-spezifisches Untersuchungsschema zur Beurteilung der Verklebungsneigung von Fels). Geomechanics and Tunnelling 5, Vol. 7, pp. 520-527, http://dx.doi.org/10.1002/geot.201400048

Thewes, M., and Hollmann, F. (2016). Assessment of clay soils and clay-rich rock for clogging of TBMs. Tunnelling and Underground Space Technology, Vol. 57, pp. 122-128, http://dx.doi.org/10.1016/j.tust.2016.01.010

Zumsteg, R., and Puzrin, A. M. (2012). Stickiness and adhesion of conditioned clay pastes. Tunnelling Underground Space Technol. 31, pp. 86–96, http://dx.doi.org/10.1680/geot.SIP13.P.005

Zumsteg, R., Plötze, M., and Puzrin, A. (2013). Reduction of the clogging potential of clays: new chemical applications and novel quantification approaches. Géotechnique 6 (4), pp. 276–286, http://dx.doi.org/10.1680/geot.SIP13.P.005

Zumsteg, R., Puzrin, A.M., and Anagnostou, G. (2016). Effects of slurry on stickiness of excavated clays and clogging of equipment in fluid supported excavations. Tunnelling and Underground Space Technology 58, pp. 197-208, http://dx.doi.org/10.1016/j.tust.2016.05.006