Daniela Garroux Gonçalves de Oliveira
Markus Thewes
Mark S. Diederichs
Lars Langmaack

DOI: 10.1002/geot.201800009

EPB tunnelling through clay-sand mixed soils: Proposed methodology for clogging evaluation

The clogging of Tunnel Boring Machine (TBM) tools by soils has long been investigated, owing to the numerous difficulties arising in shield tunnelling as a result. Its occurrence leads to operation delays owing to the frequent and lengthy interventions required to unblock the soil stuck to the excavation tools and screw conveyor. Several authors have proposed laboratory tests for evaluating the clogging potential, however, those include limitations, such as not considering the clay fraction in a soil. One of these methods is the empirical stickiness evaluation, whereby a mixer and a beater are used to define a clogging evaluation parameter. Following an extended test campaign using soils with different clay contents and minerals, it became clear that this method was not adequate to provide reliable information regarding the tendency of a soil to clog in a tunnel drive. A new device was then implemented, which adds to the first method a kinetic energy impulse via dropping of the beater from a certain height. This combination of methods could provide a reasonable approximation of the potential for clogging to occur along Earth Pressure Balance Machine (EPB) tunnel drives. This paper presents the results of the proposed combined methodology for clogging evaluation, as well as the research evolution that led to the addition of the beater dropping stage.

1 Introduction

The clogging of tools by soil was initially investigated for agriculture purposes over a century ago, as it is a particularly troublesome soil characteristic. Early investigations into soil stickiness led to one of the most widely used standard soil classifications, the Atterberg limits, which defined different soil states according to their changes in water content [1]. Later, [2] refined this classification for its application to the soil mechanics field.

Clogging in tunnel boring machines, as defined by [3] [4], occurs through a combination of four single mechanisms: adhesion of clay particles to metal surfaces, bridging of clay particles over a metal opening, cohesion of particles, and insolubility of clay minerals. The occurrence of clogging in earth pressure balance (EPB) machines (EPBMs) may cause several issues such as high torque requirements of the machine, drastic performance reductions, and lowering of advance rates. These issues result in lengthy and frequent interventions for cleaning the clogged tools, as well as additional excavation costs [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15].

The evaluation of the clogging potential and possible mitigation measures is therefore essential prior to excavation of a shield tunnel. Appropriate machine design (namely location of the foam injection system, opening ratio of the excavation interface and other particularities of the machine) and effective soil conditioning play a significant role in reducing clogging issues.

Soil conditioning is one of the most important elements of EPB tunnelling, as highlighted by several authors, e.g. [16] [17] [18] [19]. The tunnel face stability following excavation by EPB machine relies on the support pressure transferred from the excavated soil inside the chamber to the tunnel face. This is best achieved with a soil that is conditioned to a paste with soft plastic consistency and low permeability [20] [21]. Numerous additives such as water, foams, polymers, dispersants and slurries with fines, including bentonite, are used to condition the soil, with the goal of achieving the expected soil characteristics.

A considerable number of research studies have dealt with clogging in EPB machines, e.g. [5] [6] [7] [9] [11] [12] [14] [15] [22] [23]. Nevertheless, the influence of clay grain size and mineralogy in a mixed clay-sand material on soil conditioning, as well as on clogging occurrence, has not yet been subjected to extensive investigation.

This paper presents the research evolution that led to the inclusion of an extra step in the methodology proposed by [7], in order to assess the clogging potential by means of a Hobart mixer. Tests were conducted with pure clay and mixed sand-clay soils, assembled in the laboratory, adding only water as a conditioner and changing the clay contents and minerals. The test results also disclose certain preliminary information regarding the influence of clay/clay mineral content in a mixed clay-sand soil. Soils assembled in the laboratory were selected to ensure reproducibility, allowing for evaluation of the new combined methodology. The results were compared to the universal clogging evaluation diagram from [8], indicating closer fitting between this empirical diagram based on real tunnel drives along pure clay soils and the results obtained using the proposed combined methodology.

2 Clogging mechanisms and evaluation

Issues with clogging have long been addressed for tunnel drives in clayey soils. [24] demonstrated that clay adhesion to metals exhibits a strong correlation between soil mechanical parameters, and increased adhesion occurs with increased soil plasticity, or consequently, a decreased activity index, as well as being influenced by the undrained shear resistance of the material. Clogging mechanisms were explained in detail by [3], who defined four mechanisms, as mentioned in the introduction: adhesion, bridging, cohesion and not dissolving. Of these four mechanisms, adhesion of the particles to the metal surface is the most significant factor leading to clogging, and this adhesion can be classified as tangential or normal.

Ref. [25] offered a review on the occurrence of clogging in tunnel boring machines, reminding readers that a standardized method for evaluating clogging potential does not yet exist, particularly for mechanized excavations. The authors of this paper divided the clogging evaluation methods into two main approaches, the first being an empirical evaluation based on clogging occurrence in tunnel drives. Several empirical charts have been proposed to evaluate clogging, such as those by [26], [27] and [28] for clogging evaluation in Mixshield specifically, as well as a universal chart by [8].

The universal chart developed by [8], for instance, considers the plastic and liquid soil limits, the changes in water content and consistency index (Ic), correlating that with distinct clogging potential ranges, from absent (lumps or fines dispersing) to strong clogging. Data from several projects with clogging occurrences were compiled for the design of this graph. However, one of the limitations of this correlation was not considering changes in the clay percentage, for instance, in the case of mixed soils. Also, the used data are from soils with maximum values for plasticity index around 70 %, not being considered data from highly plastic soils.

The second approach to evaluating clogging is the direct assessment of particle adhesion to a metal surface, measured with different laboratory devices. [3] constructed a separation test device to determine the clay adhesion when a piston is pulled away vertically from a soil sample. Several tests were conducted, and the results demonstrated that the normal adhesion is directly related to the presence of clay minerals, with greater normal adhesion reported for samples containing swelling clays (such as Smectite).

[6] proposed a classification scheme to determine the clogging potential of different clays based on the "cone pull-out test", defining an adherence value based on the energy required to pull a metallic cone out of the soil following compaction by a standard proctor device. The results were then plotted against the soil consistency. Because the cone is rotated prior to being pulled out, the adhesion measurements are assumed to have both a normal and a shear component.

[7] used a Hobart mixer with a B-flat beater, with the intention of qualitatively evaluating the soil clogging potential. This Hobart mixer is used in concrete laboratories and the bakery industry and is available worldwide. For the first tests a 20-l capacity Hobart mixer was used, and later a 5-l version [29].

This simple method consists of weighing the B-flat beater with any sticky soil on it, following rotation inside a mixing bowl, and comparing this with the total soil mixture weight. The mixer is rotated at speed level 1 at 100 rpm for 3 min, which, according to [7] and [30], is sufficient to "achieve mixture homogeneity at a larger scale and a steady state for the amount (mass) of clay sticking to the mixing paddle", although it does not provide a uniform water distribution at the particle scale.

From this comparison between the mass of the material stuck in the beater and the total material mass, it is possible to obtain an empirical stickiness ratio (λ), as provided by Eq. (1):

$$\lambda = G_{MT}/G_{TOT} \quad (1)$$

where G_{MT} refers to the mass of the material stuck in the beater and G_{TOT} is the total soil mass.

[31] also compared the results obtained for the clogging evaluation parameter λ to the diagram proposed by [3], to be applied in the clogging evaluation of mixshields. The authors defined different clogging potential levels corresponding to varying values for the parameter λ: low ($\lambda < 0.2$), medium (λ between 0.2 and 0.4) and high ($\lambda > 0.4$).

[7] developed an additional device to evaluate soil clogging potentials: the plate shear test. Using this device, the tangential adhesion was measured by rotating a plate tangentially to the soil sample, providing a parameter for evaluating the sliding resistance of the material against the steel surface, which, according to the authors, has a greater influence on the clogging potential than normal adhesion resistance. Numerous soil mixtures were tested, together with chemical additives, as explained by [7] [31] [29].

[13] conducted laboratory tests on three different clayey natural soils and explained that the samples were tested not only as an initially powdered fraction, but as pre-moulded lumps, as this would provide a closer approximation to the reality of the excavation of an EPB machine. According to the authors, it is possible that excavated soil may not be reduced into a completely crushed form, but rather may detach in lumps of variable sizes, depending on the machine cutterhead openings, which are usually between 10 and 30 mm in diameter. In this case, the conditioning remains only around the surface of the lumps and is not completely homogenized. [13] also concluded that tests should always be carried out using only water as the conditioning agent in order to understand the mixture behaviour fully and for comparison with the conditioned material results.

[15] compared the results from a piston pull-out test using 35 clayey soils in two distinct consistency indexes with the four main four evaluation charts, achieving a high match with the graph from [27], which was not observed with the other charts.

These direct measurement methods to evaluate clogging potential did not succeed, yet, to be directly validated with real tunnel drives, or to have a good correlation with the clogging diagram from [8], the diagram currently applied in the tunnel industry. These methods did not consider the changes in the clay fraction, failing to evaluate mixed soils.

3 Materials and methods

The tested samples were soils that were reconstituted in a laboratory, so that all of the variables could be fully controlled. Although that natural soils differ from reconstituted laboratory samples, the intention here was to validate methodologies under a controlled scenario, avoiding the local variability found in natural materials.

It was decided to focus on two different clay minerals, which would represent the two plasticity extremes: Na-bentonite (highly plastic) and kaolinite (very low plasticity). A larger number of tests were conducted with kaolinite, due to the ease and stability of dealing with this material.

Furthermore, several tests were conducted with mica flakes. The initial intention was to recreate a gneissic residual soil from the São Paulo Basin in Brazil, which is a typical tropical ground that presented numerous issues while being excavated by an EPB machine [32] [33]. Kaolinite is a typical clay mineral for tropical residual ground. Mica is also an important component, leading to the inclusion of a short chapter on this research. Therefore, another reason that kaolinite was selected as the main tested clay mineral was so that certain correlations between tropical residual ground and clogging occurrence could later be drawn.

The Hobart mixer testing methodology was continually modified throughout the research, until it was acknowledged that an additional stage was required leading to the assemblage of a new device, namely the “Adhäsive Tone Untersuchung RUB/Queens (ATUR)” (RUB/Queens Clay Adhesion Tool). The description illustrated below is the final methodological sequence, which achieved superior results overall; however, modification of this methodology is still under investigation and improvement.

3.1 Reconstituted soils

Table 1 presents the main characteristics of each tested soil component, including the types of kaolinite (always cited as K) and bentonite (always cited as B). Figure 1 illustrates the grain size curve for the sand components used in this research. There were three types of grain size distribution for the sand fraction: “Sfine”, “Fine-Medium Sand” and “12”. All three of them are quite similar in terms of grain size distribution. Table 2 presents a summary of all the tested artificial soils, including their Atterberg limit values.

3.2 Hobart mixer methodology – original version

The tests for evaluating the clogging potential were conducted using a Hobart mixer with a 5-l capacity, as shown in Figure 2, together with a B-flat beater, as suggested in [7] and [29].

For each sample, the soil component was initially weighed with a 0.1-g precision scale, and subsequently mixed according to the proportions defined in Table 2. De-ionized water was added to achieve the initial water content, which was defined for each sample based on its consistency, usually starting with consistencies no higher than 1 in order to avoid damaging the machine with hard soils. There was a total waiting period of 24 h prior to starting the tests, in order to allow time for the clay minerals to react, or swell, as the case may be, enabling improved moisture homogenization. The material was maintained in a closed recipient in order to avoid moisture loss.

In total, six to twelve tests were carried out for each sample, with the water content being increased every time until the consistency reached a level close to zero. For each increase in moisture content in the same mixture combination, the B-flat beater and total soil sample were weighed, providing the parameter λ_0.

Following each test, for every water content increase, the moisture content was verified following the methodology defined by [34], thereby verifying whether the mixture was moisturized homogenously. The moisture contents of

Table 1. Main characteristics of each component of constituted soils

Product specification	Supplier	Spec. grav.	Chemical comp.	Specific Surface [m^2/g]	Cation exc. capacity [meq./100 g]	pH	Moisture [%]
Silica sand*1	Bell & Mackenzie	2.65	SiO_2	–	–	6–7	–
Kaolinite – EPK Kaolin*1	Edgar Minerals	2.65	Al_2O_3, $2SiO_2$, $2H_2O$	28.52	4.5	5.8	Max. 1
Na-Bentonite – Volclay® 325 mesh*1	American Colloid Company	2.35	(Na,Ca)0.33 (Al1.67Mg0.33) $Si_4O_{10}(OH)2$ nH_2O	0.09–1.8	>70	8.5–10.5	Max. 12
Phlogopite Mica PD900*1	LKAB	2.8	$KMg_3(AlSi_3O_{10})$ $(OH,F)_2$	0.3	No appreciable CEC	9	Max. 1
Silica sand*2	Euroquarz	2.65	SiO_2	–	–	6.5–7	–
Kaolinite GHL KS 80*2	Georg H. Luh GMBH	2.62	Al_2O_3, SiO_2, Fe_2O_3	18.2	–	4.5–9.5	0.6–2
Active Na-Bentonite IBECO B1*2	Imerys Civil Engineering	2.65	Al_2O_3, SiO_2, Fe_2O_3, MgO, CaO, K_2O, Na_2O	600–800	70±10	10	11±3

*1 – Initial tests presented in Item 4.1; *2 – Final tests presented in Item 4.2

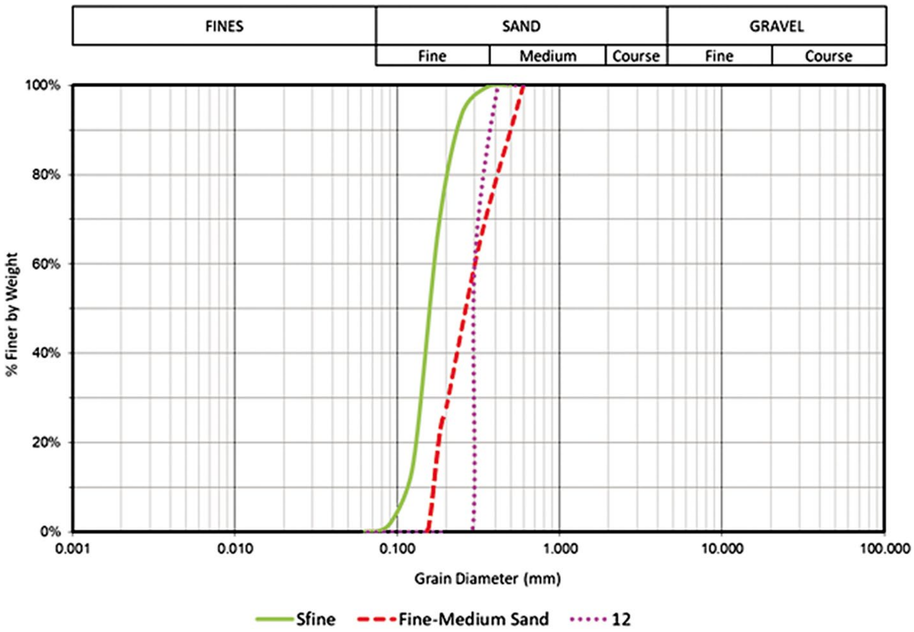

Fig. 1. Grain size distribution only for the sand portion of the soil mixture presented in Table 2. This sand portion was mixed with different clay minerals or mica flakes, in different proportions, as listed in Table 2

Table 2. Tested samples with respective proportions of minerals and Atterberg limits

Sample ID	Sand type (Fig. 1)	Sand (%)	Kaolinite (%)	Bentonite (%)	Mica (%)	WL (%)	WP (%)	PI (%)
FMK20	Fine-medium	80	20	–	–	24	15	9
FMK25	Fine-medium	75	25	–	–	26	16	10
FMK35	Fine-medium	65	35	–	–	29	18	11
FMK40	Fine-medium	60	40	–	–	32	19	13
12K3	12	70	30	–	–	22	13	9
12B1	12	80	–	20	–	90	24	65
12B2	12	60	–	40	–	194	36	158
12KM1	12	25	60	–	15	41	24	17
12KM2	12	10	60	–	30	47	31	16
Ksfine30	Sfine	70	30	–	–	22	16	6
Ksfine50	Sfine	50	50	–	–	32	21	11
Ksfine70	Sfine	30	70	–	–	44	29	16
K100	Sfine	0	100	–	–	62	40	22

Fig. 2. Hobart N50 mixer and B-flat beater

samples, as measured from the beater and mixing bowl, were compared. As these samples often did not exhibit equal moisture contents, the original methodology had to be modified; the speed of the mixer was increased from 139 rpm (speed level 1) to 285 rpm (speed level 2) for at least a couple of seconds until the mixture was homogenized, and then returned to speed level 1 for 3 min.

3.3 Combined methodology – Hobart and ATUR

Following several tests, as originally conceived by [7], it was realized that for certain consistencies, any vibration or drop in the B-flat beater would be sufficient to totally or partially remove the soil stuck in the beater, as illustrated in the results of item 4.1. Therefore, a trial was initiated in order to determine different means of dropping the beater from a certain height. Initially, this was achieved by drop-

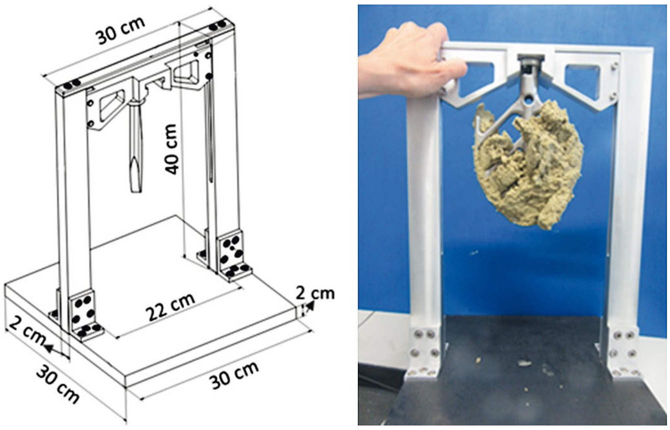

Fig. 3. ATUR device: drawing with dimensions on the left and B-Flat beater with soil stuck to it on the right

ping the beater firstly on top of a plastic bowl, and then on top of a Casagrande cup base, which has a standardized material and size specification [35], leading to the first results demonstrated in item 4.1.

Every time the beater hit the surface, the tool was weighed again, initially resulting in three additional measures of the empirical clogging evaluation parameter λ, denoted by λ_1, λ_2 and λ_3, representing the values achieved after 1, 2 and 3 blows, respectively. The impact that the beater with the soil suffered by dropping the beater into a plastic bowl was lower than when dropping it onto the Casagrande cup base; therefore, due to the lack of a steady standard, the preliminary results are merely illustrative.

Finally, a device was assembled in order to provide the B-flat beater with a free fall from the same height (37 cm) along the same axis. Figure 2 illustrates this new assembled device, the denominated ATUR, from research cooperation between Queen's University in Canada and Ruhr Universität Bochum in Germany.

Later, a calibration was conducted considering mainly pure kaolinite samples for different consistency indexes, as shown in item 4.2. The final methodology sequence is schematically presented in Figure 4. The sequence may undergo certain changes in the future, especially considering that a total of seven drops (λ_7) was necessary to achieve similar results to three drops (λ_3) when using the Casagrande cup base, which has a higher material stiffness.

4 Results and discussion

4.1 Initial results – preliminary phase

Following the Hobart testing methodology, a total of 35 samples were tested during the preliminary testing phase. Firstly, the results for the mixtures with a fine-medium sand mixed with kaolinite are illustrated, compared to the original method of simply weighing the B-flat beater, using the initial dropping version without a reliable method for dropping the beater. Figure 5 presents the results of the empirical clogging parameter λ for samples with increasing clay contents. The EPB consistency range (between 0.4 and 0.75) is illustrated with a grey square in the images.

It should be noted that the λ values tend to increase with increasing consistency beyond 0.8, when the clay fraction increases from 20 to 25 %; these values continue to increase as the clay content increases. For these initial tests, although the new dropping adaptation was still

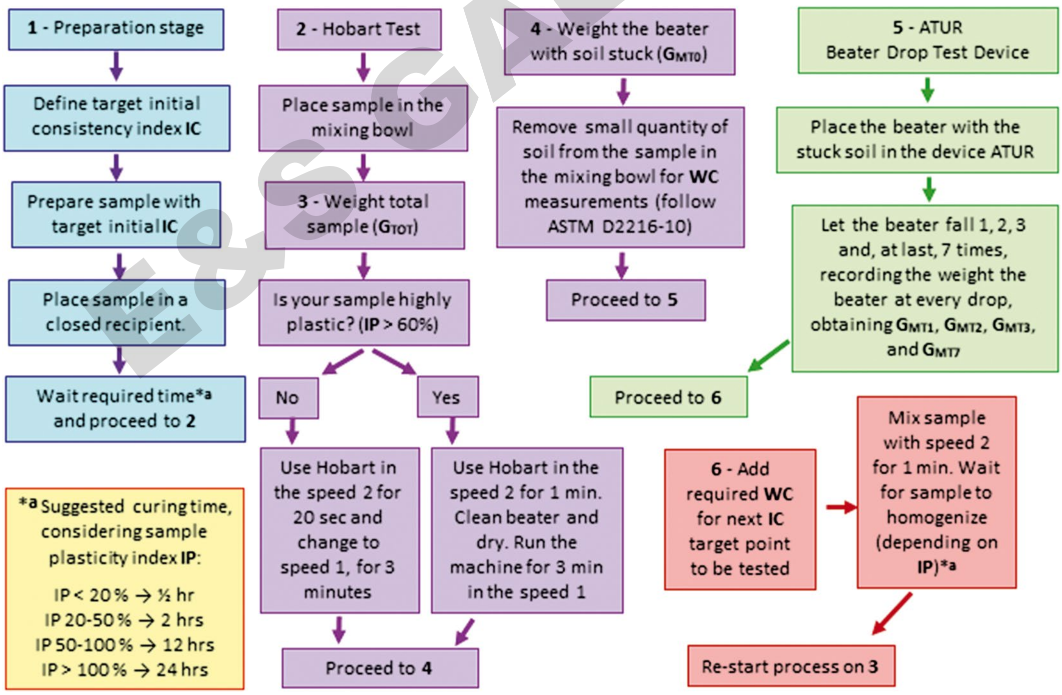

Fig. 4. Schematic sequence for combined methodology for clogging evaluation with Hobart and ATUR, considering the following parameters: IC (consistency index); IP (plasticity index); WC (water content); and the clogging evaluation parameters: GTOT (total mass of sample); GMT0 (total mass of soil stuck in the mixing tool); GMT1,2,3,7 (mass of soil after dropping the beater 1, 2, 3 and 7 times, respectively). The curing time is considered the time that the sample is left to rest in a closed recipient, to achieve moisture homogenisation

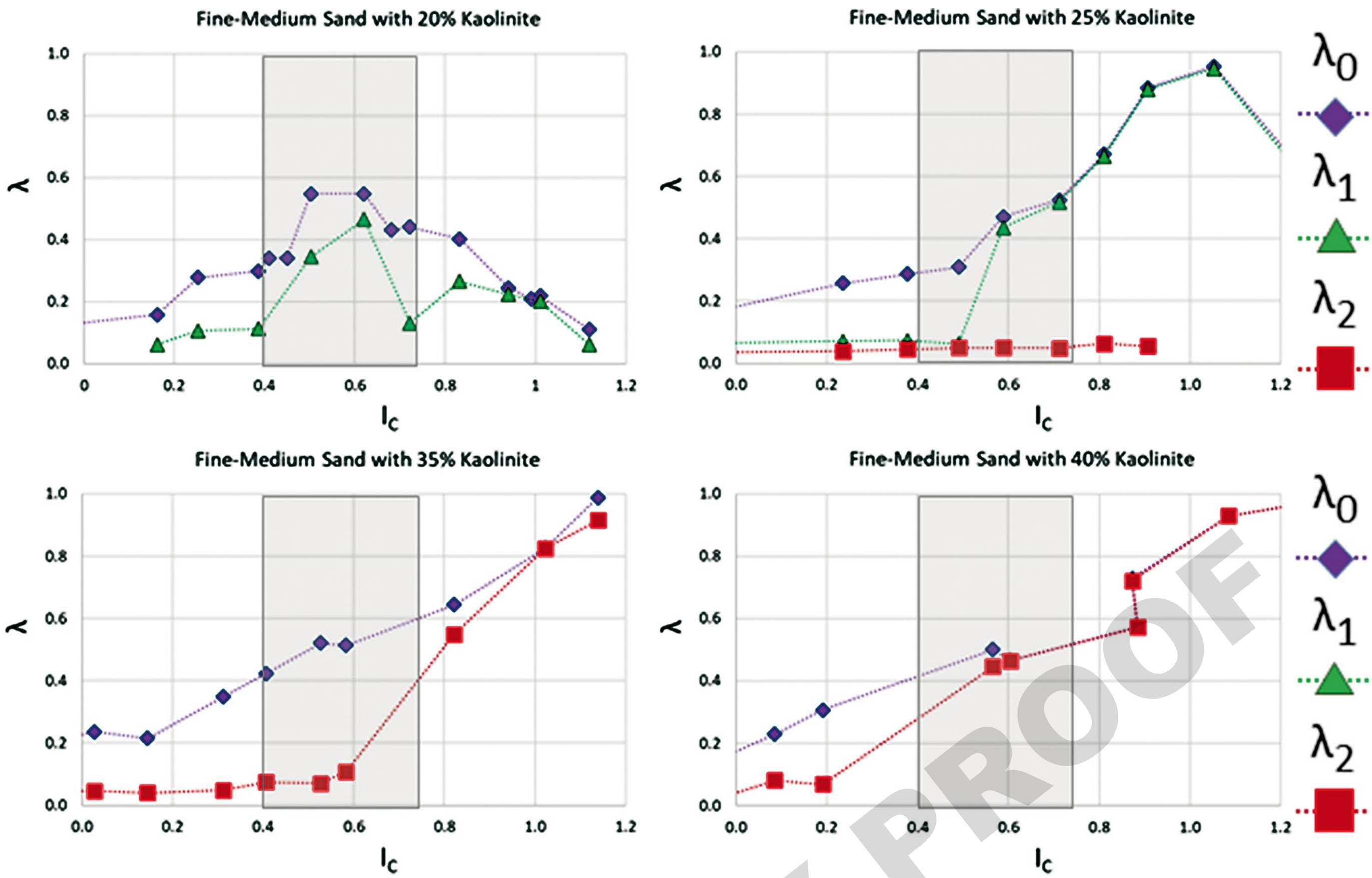

Fig. 5. Fine-medium sand mixed with 20, 25, 35 and 45 % kaolinite

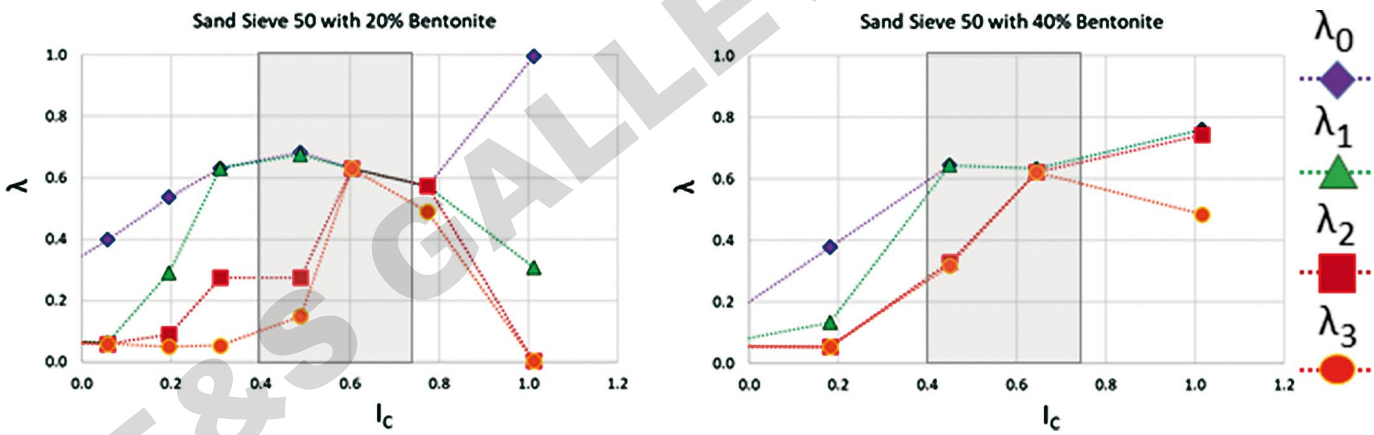

Fig. 6. Comparison of samples 12B_1 and 12B_2 with sand sieve 50 and bentonite

crude, completely distinct λ_0 and λ_2 values were reported at the 25 and 35 % clay content levels along the EPB consistency range.

Figure 6 presents the results of bentonite clay with sand (grain size denominated 12 in Figure 1), comparing two samples containing 20 and 40 % bentonite, respectively, each mixed with sand of sieve number 50. Following several drops, the soil was totally detached from the beater for consistencies higher than 0.8, which is similar to the results obtained for samples containing kaolinite. This observation was more pronounced for the sample containing 20 % bentonite than for that with 40 % bentonite.

Following several tests, particularly for low plasticity samples with a relevant sand contribution, the majority of the soil stuck in the beater would be easily removed with any vibration or mixing tool impact. Likewise, for certain consistency ranges and soil combinations, most of the soil would remain stuck, even once the beater was abruptly jolted. Figure 7 illustrates four cases for two different clay mineral samples.

On the top left is an example of a sample with 30 % kaolinite mixed with fine sand and on the top right, a mixture of 20 % bentonite with fine sand, both with a consistency index of 1 (equal to the plastic limit). In this case, without any beater impact, the sample would be classified as high clogging ($\lambda_0 = 0.9$ and $\lambda_0 = 1.0$ for the kaolinite and bentonite samples, respectively). However, after always dropping the sample from the same height, once (λ_1), twice (λ_2), or even three times (λ_3), there was a significant decrease in the soil stuck in the beater, leading to an ab-

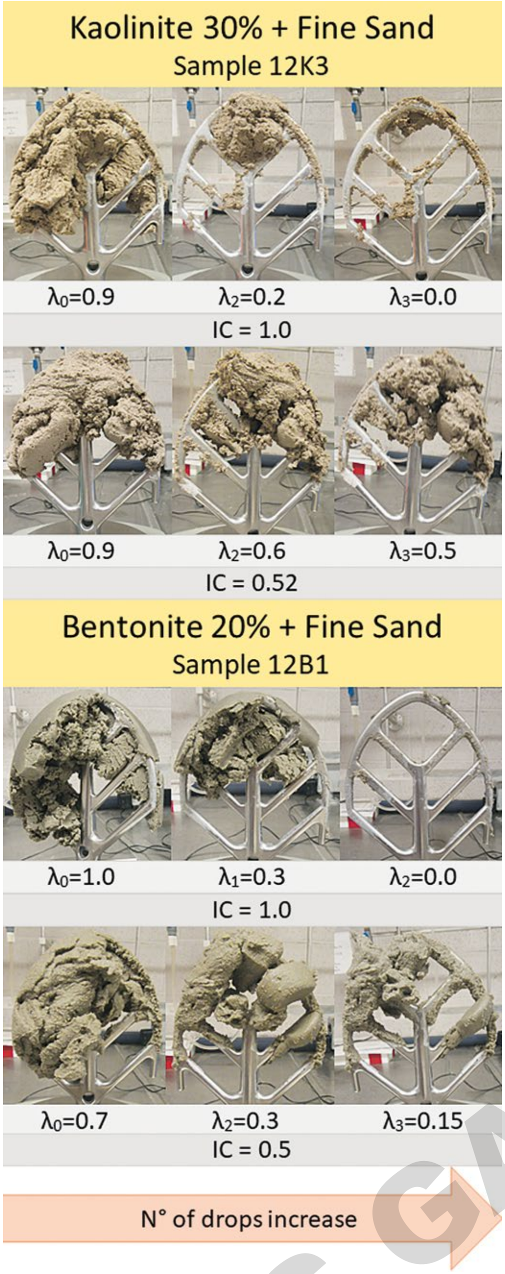

Fig. 7. Two tested samples with distinct consistencies (IC): on top, a kaolinite mixture and at the bottom, a bentonite one. The arrow indicates the direction that increases the number of drops, providing different values for λ (λ0 = zero drop; λ1 = one drop, and so on)

sence of clogging. Nevertheless, for lower consistencies, as seen in the bottom of the figure, a significant amount of soil was present in the beater, even after several joltings of the mixing tool.

This same behaviour was observed during several tests: Material was frequently being removed from the beater with the extra blow stage for stiff to very stiff soils higher than the EPB consistency range, and for very soft soils lower than the EPB consistency range. In these cases, the samples did not exhibit the same high clogging results from the original λ_0 value. Mostly, for both cases of clay, it was observed that, within the ranges where the adhesion of the clay to the metal surface was significant, the beater dropping did not really affect the value of parameter λ_0. This observation occurred mainly for soft soils with consistency values of 0.5 and 0.8, characterized by the diagram of [8] as a strong clogging area.

For stiffer consistencies, detachment occurred in lumps, while for softer consistencies, it occurred as a sticky and liquid paste, illustrating the strong connection between the consistency indexes and clogging tendency. Likewise, it is demonstrated that this original methodology may exhibit a superior fit for samples with higher clay contents or pure clay materials, and for a certain consistency range, mainly between 0.5 and 0.8. As the consistency values increase or decrease beyond this range, the additional stage of dropping the beater could provide more accurate results for the clogging potential, compared to the graph from [8].

Figure 8 presents all of the samples plotted in the graph of [8]. In the top graph, the samples have not received any jolting, and on the bottom are plotted the results after three beater drops from the same height. There is improved 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_0). However, too many discrepancies can be detected and the lack of a solid procedure for dropping the beater certainly influenced the results.

Furthermore, several tests were performed including mica flakes, as previously mentioned, in order to represent the typical residual soil originating from a gneissic rock, which is rich in this mineral. The results are presented in Figure 9, and the λ values are quite similar at consistency values below 0.7. For higher mica flake contents, λ decreases slightly at consistency values above 0.7. The values of λ_1, λ_2 and λ_3 decrease more evidently with higher mica flake contents.

Presumably, the mica flakes functioned as a lubricant, detaching the material from the metal surface and thereby diminishing its adherence. This phenomenon was even more evident when the beater was dropped, which can be related to the low binding forces between the mica flake layers.

These results could even be compared to the EPBM excavation along a gneissic residual soil, such as that of the São Paulo Metro, Line 5, Lot 3, Brazil ([32] and personal communication). At this site, stretches with higher biotite content (originally from the dark gneissic bands) would not present clogging issues, even with the presence of clay minerals, while excavated sections with clay but without mica flakes (light bands from the gneissic parent rock) exhibited clogging. However, there was a higher incidence of face instability along portions with higher mica content, which was less apparent along stretches with less mica flakes and higher clay content.

4.2 Combined methodology – calibration and initial results

The following tests demonstrate the initial results obtained using the combined methodology of the Hobart mixer together with the dropping stage conducted with the new device, ATUR. The concept for the dropping stage is schematized in Figure 10. A clayey material would possess adhesion stress, maintaining the sample attached to the metal surface (top of figure) along a certain surface

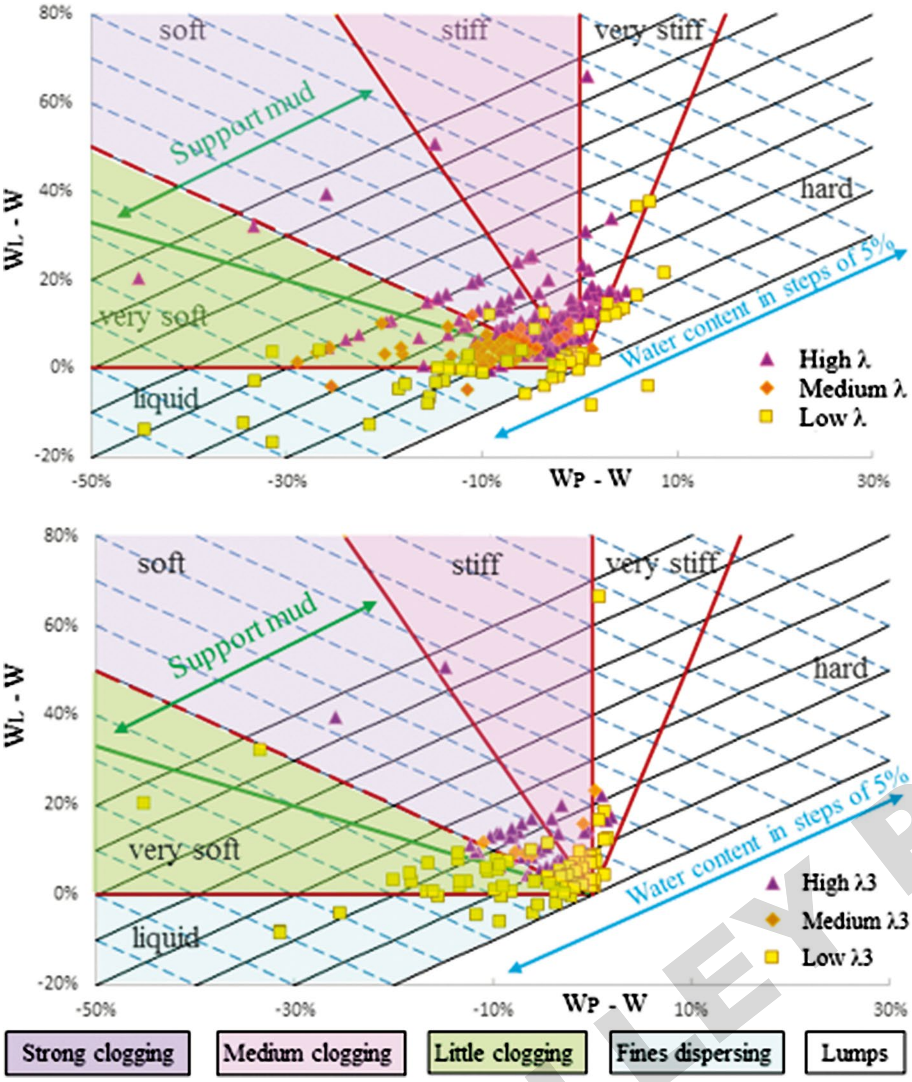

Fig. 8. Results from preliminary testing phase plotted in the clogging potential universal graph (modified from [8]). The top chart represents the samples without any beater dropping, as originally defined by [7], while the bottom chart presents the modified version after three beater drops

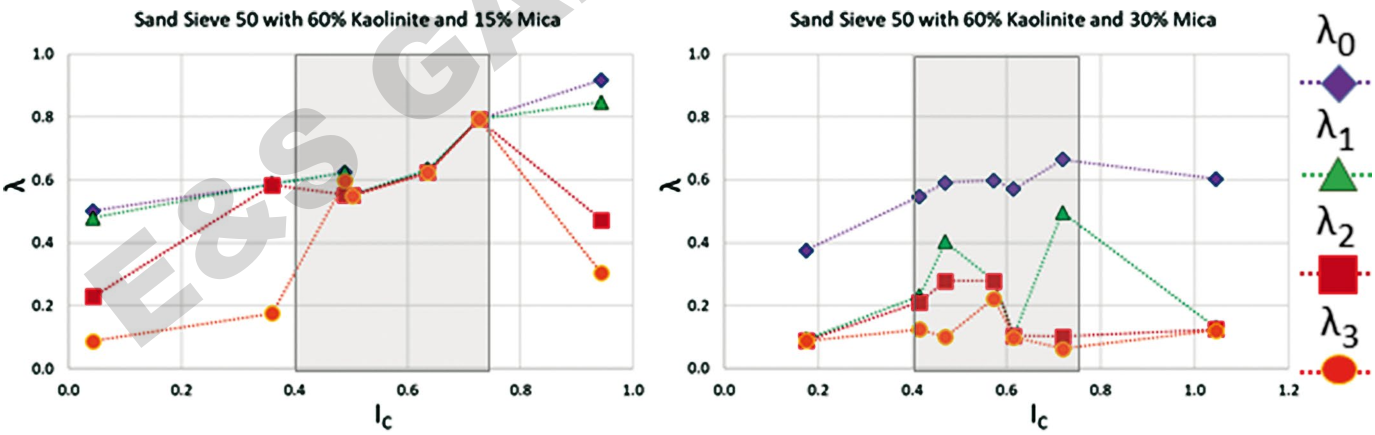

Fig. 9. Comparison between samples 12KM_1 and 12KM_2, with fixed 60 % kaolinite, and 15 and 30 % mica flakes (phlogopite), respectively

area, which would depend on certain variables, such as consistency and adhesion, as already investigated by numerous authors [3] [6] [14] [15] [30].

If a certain counterbalance of kinetic energy is exerted, as in the case of the laboratory tests, the beater drop, or in a real EPB tunnel drive, the machine cutterhead rotation and soil flow inside the excavation chamber (therefore, not static), the clogged material would either remain stuck or not, depending on its clogging potential. This can be verified during laboratory tests, and later correlated with the empirical chart from [8], which is based on real tunnel drive data.

When clogging is pronounced, the counterbalance of kinetic energy (red arrow in Figure 10) would not be sufficient to detach the sample from the surface. Ideally, this counterbalance kinetic energy should be calibrated with a

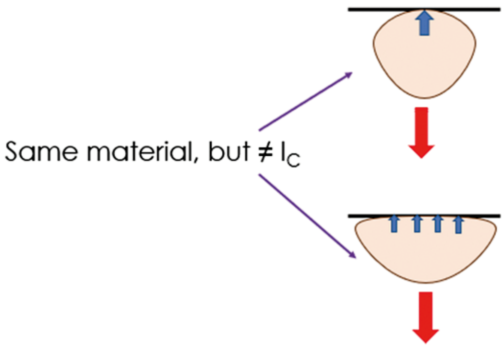

Fig. 10. Scheme of drop stage added to Hobart mixing methodology. A soil sample (represented by the shape in pink colour) with two different consistency indexes exerts a certain adhesion force (represented by the blue arrow), which attaches this sample to a metal surface (black line). Depending on the clogging potential and responding to a counterbalance kinetic energy (red arrow), this soil may or may not detach, separating from the metal surface

large amount of tunnel data, which could undoubtedly increase this calibration refinement.

Thereafter, tests were conducted using the combined methodology, initially only dropping the beater up to three times, with the results illustrated in Figure 11. The samples were mixed with very fine sand, denoted as “sfine” in Figure 1. From these three graphs (30, 50 and 70 % kaolinite) it can be observed that at higher (Ic > 0.75) and lower (Ic < 0.4) consistencies, the differences between λ_0 and λ_3 are greater, precisely because clogging should not be expected at these consistencies. This demonstrates that the empirical stickiness parameter λ_0 does not reflect the expected clogging potential.

The final stage involved calibrating the number of beater drops with the ATUR device. Pure kaolinite soils were tested and the results were crossed with the clogging potential, as defined in the universal chart of [8]. The target consistency values were defined considering the limits among distinct clogging potentials for this chart (Figure 12). The results are displayed in Table 3, where the cells are coloured according to the clogging potential (yellow – low; orange – medium; red – high). The limits defined for these ranges were adjusted to better fit the ranges from the graph of [8], with λx values (x representing any number of drops, including none as 0): < 0.2 = low clogging potential; between 0.20 and 0.46 = medium clogging potential and higher than 0.46 = high clogging potential. These values differ slightly from those defined by [7].

As can be observed from Table 3, following seven beater drops using the ATUR device, it was possible to obtain very close results to those defined by [8] with the universal chart. If the results without any beater dropping are considered (λ_0) for all the tested consistency indexes, the clogging would be high, and the results would not correspond with those expected from this chart. Furthermore, kaolinite is a very low plasticity clay and should not be expected to exhibit such extensive clogging for this wide range of consistency values. Thus, these values certainly need to be adjusted with additional obtained data and crossed with tunnel drives.

Certain values of λ_7 (marked in bold and italics in the table) still do not entirely fit the chart of [8]; nonetheless, the results should be closer to the reality of clogging oc-

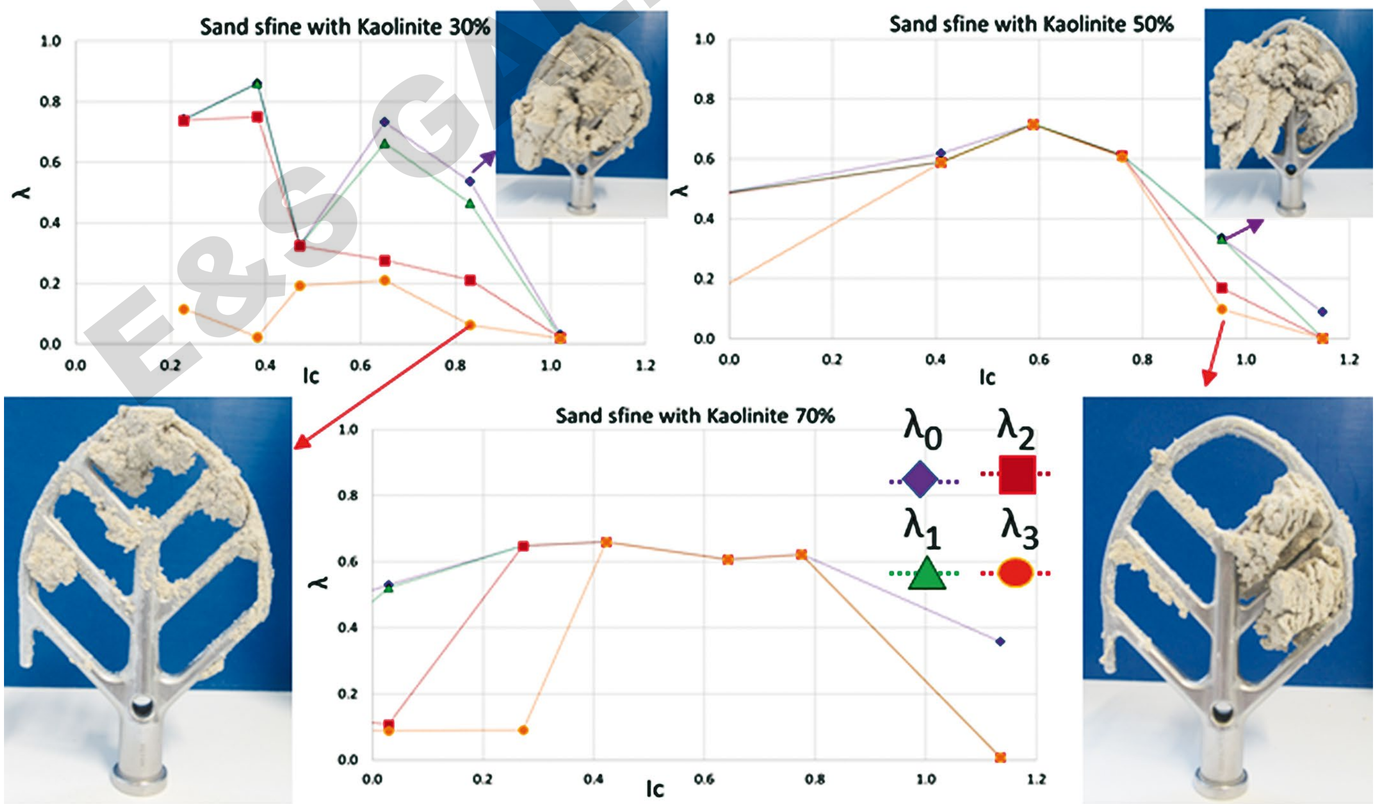

Fig. 11. Results from three different samples, containing 30, 50 and 70 % kaolinite, showing four different empirical stickiness values of λ

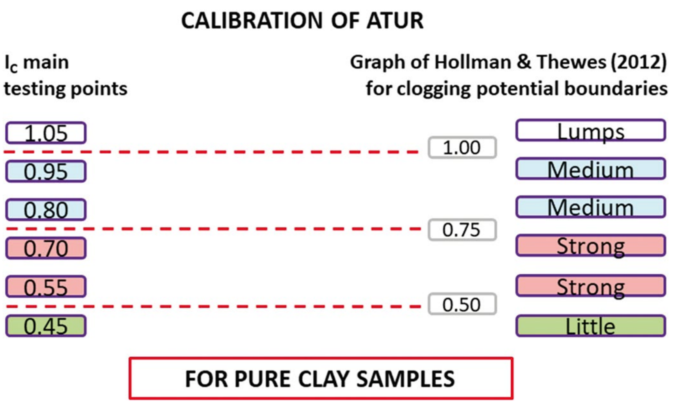

Fig. 12. Main testing target points for the initial ATUR calibration, considering clogging potential boundaries as defined by chart of [8], with limits presented on the right

currence in EPB machines than those of the original empirical stickiness evaluation using the Hobart machine alone, as proposed by [7].

At present, the addition of an extra final stage is also under consideration, characterizing the ease of removing the soil from the beater and mixing bowl. Although this would provide an imprecise parameter, it may aid in distinguishing between low potential clogging and a lump, as in the second case where the soil is easily detached from both the beater and bowl by hands and with the use of water only, while the first option, namely a large amount of soil, sticks to the fingers, and soap is required for the cleaning process. Furthermore, this could later be correlated with the ease/difficulty of realising interventions, as a soil that is challenging to clean and remove from the metal parts of the machine would imply lengthier interventions.

Table 3. Results for initial calibration of Hobart + ATUR values compared with clogging potential ranges of [8] (indicated as H&T in the table). The colours in the cells are as follows: red for high clogging potential, orange for medium clogging potential, yellow for little clogging potential and white for occurrence of lumps

Test ID	Test N°	Water content	IC	λ_0	λ_1	λ_2	λ_3	λ_7	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

The process of clogging during EPB tunnelling of clay soils is complex and influenced by several variables. These variables are not only directly connected to the soil or underground water properties, but also interrelated with the conditioning additives used during the process, the machine itself, including the design of the cutterhead openings, positioning and shape of excavation tools, locations of foam injectors, foam generator, machine torque, and other details, with the further addition of high temperatures and pressure. It is a challenging task to combine all these variables into a holistic model. With limited work previously conducted in this research area, particularly that can be directly applied to EPB operations, issues of clogging tend to lead logically to a trial-and-error approach during actual tunnel excavation.

A preliminary investigation, consisting mainly of a preliminary clogging assessment prior to excavation, may offer qualitative characterisation of the soil and its expected behaviour when properly conditioned, which could possibly mitigate future clogging issues. Complex and expensive laboratory methods or devices are undoubtedly necessary for understanding the clogging process, particularly concerning soil adhesion. However, this combined methodology offers as a main advantage practicability and ease, with the aim of reaching a higher number of researchers as well as tunnel professionals, thereby providing the ability to assess clogging potential easily, and enable comparison with other data samples.

It has been demonstrated that data produced using the Hobart mixer on its own does not reflect the clogging potential for certain consistency ranges or lower clay contents in the case of mixed clay-sand soils. The opposite effect was illustrated using the combined methodology with the addition of the extra dropping stage, which can achieve satisfactory results. Undoubtedly, the greatest advantage of this methodology is the very simple and practical procedure involved, along with the fact that a Hobart mixer is a device that can easily be acquired worldwide.

Furthermore, the combined methodology provides the possibility of evaluating the efficiency of soil conditioners, such as foam and polymers. In this study, the authors evaluated the effects of mica flakes in the soil, which were considered as part of the soil. It could even be speculated that for scenarios with high mica contents, as in the example of excavation along a weathering ground product of a mica-schist, clogging issues are not expected to occur, even with high clay contents. Moreover, the results could indicate that by adding mica flakes in the front of the machine, if that were physically and economically feasible, could imply a decrease in clogging issues.

Device calibration can be performed with pure clay materials, changing their consistency values as demonstrated in section 4.2. Later, a standardised base can be defined, as was carried out with the Casagrande cup base [35]. With the continuation of this research and further calibration with real tunnel drives, it is expected that a reasonable and simple clogging assessment methodology can be achieved, which can be correlated to other proposed clogging evaluation methods.

Acknowledgments

Support for this research was received from the Natural Science and Engineering Research Council (NSERC), Canada and funding from Queen's University. The authors would like to acknowledge the support of the Collaborative Research Center SFB 837, "Interaction Modelling in Mechanized Tunnelling", funded by the German Research Foundation (DFG). We are also grateful to the technical staff at Ellis Hall, from the Geotechnical Laboratory of the Civil Department at Queen's University, for providing laboratory space, and to the laboratory team at TLB, at Ruhr University Bochum. Acknowledgments are also extended to the LKAB minerals, represented by *Magnus Johansson*, who kindly provided the phlogopite flakes. Special thanks to *Yvonne Ueberholz* from Ruhr University Bochum, for the device assemblage, and Dr. *Mario Galli* from Porr Deutschland GmbH, for assistance with the scientific device name.

References

[1] *Atterberg, A.*: Die Plastizität der tone. Int. Mitt. Bodenkunde 1 (1911), S. 10–43.

[2] *Casagrande, A.*: Research on the Atterberg limits of soils. Public Roads 13 (1932), S. 121–130.

[3] *Thewes, M.:* Adhäsion von Tonböden beim Tunnelvortrieb mit Flüssigkeitsschilden. PhD Thesis, Bergische Universität Wuppertal, 1999.

[4] *Thewes, M.:* Schildvortrieb mit Flüssigkeits- oder Erddruckstützung in Bereichen mit gemischter Ortsbrust aus Fels und Lockergestein. geotechnik 27 (2004), S. 214–219.

[5] *Sass, I, Burbaum, U.*: A method for assessing adhesion of clays to tunneling machines. Bull Eng Geol Environ 68 (2009), S. 27–34.

[6] *Feinendegen, M., Ziegler, M., Weh, M., Spagnoli, G.*: Clogging during EPB-tunnelling: Occurrence, classification and new manipulation methods. ITA-WTC2011. Helsinki: ITA-AITES, 2011.

[7] *Zumsteg, R., Puzrin, A. M.*: Stickiness and adhesion of conditioned clay pastes. Tunnelling Underground Space Technol 31 (2012), S. 86–96.

[8] *Hollmann, F., Thewes, M.*: Evaluation of the tendency of clogging and separation of fines on shield drives / Bewertung der Neigung zur Verklebungsbildung und zur Feinkornfreisetzung bei Schildvortrieben. Geomechanics and Tunnelling 5 (2012), No. 5, S. 574–580.

[9] *Hollmann, F., Thewes, M.*: Assessment method for clay clogging and disintegration of fines in mechanised tunnelling. Tunnelling and Underground Space Technology 37 (2013), S. 96–106.

[10] *Hollmann, F., Thewes, M., Weh, M.*: Einflüsse von Verklebungen auf die Materialförderung von Schildvortrieben. Tunnel Nr. 3/2014), S. 10–19.

[11] *Thewes, M., Hollmann, F.*: TBM-specific testing scheme to assess the clogging tendency of rock / TBM-spezifisches Untersuchungsschema zur Beurteilung der Verklebungsneigung von Fels. Geomechanics and Tunnelling 7 (2014), No. 5, S. 520–527.

[12] *Thewes, M., Hollmann, F.*: Assessment of clay soils and clay-rich rock for clogging of TBMs. Tunnelling and Underground Space Technology 57 (2016), S. 122–128.

[13] *Peila, D., Picchio, A., Martinelli, D. Dal Negro, E.*: Laboratory tests on soil conditioning of clayey soil. Acta Geotechnica 11 (2016), S. 1061–1074.

[14] *Basmenj, A.K., Mirjavan, A., Ghafoori, M. Cheshomi, A.*: Assessment of the adhesion potential of kaolinite and montmorillonite using a pull-out test device. Bull Eng Geol Environ (2016), S. 1–13.
[15] *Khabbazi, A., Mohammad, G., Azali, S.T., Cheshomi, A.*: Experimental and laboratory assessment of clogging potential based on adhesion. Bull Eng Geol Environ (2017), S. 1–13.
[16] *Maidl, U.*: Erweiterung des Einsatzbereiches von Erddruckschilden durch Konditionierung mit Schaum. PhD Thesis, Ruhr-Universität Bochum.
[17] *Langmaack, L.*: Advanced technology of soil conditioning in EPB shield tunnelling. North American Tunneling 2000, S. 525–542. CRC Press, 2000.
[18] *Merritt, A.*: 2004, Conditioning of clay soils for tunnelling machine screw conveyors. PhD Thesis, University of Cambridge, 2004.
[19] *EFNARC*: Specification and Guidelines for the use of specialist products for Mechanised Tunnelling (TBM) in Soft Ground and Hard Rock. UK: EFNARC, 2005.
[20] *Herrenknecht, M., Thewes, M., Budach, C.*: The development of earth pressure shields: from the beginning to the present / Entwicklung der Erddruckschilde: Von den Anfängen bis zur Gegenwart. Geomechanics and Tunnelling 4 (2011), No. 1, S. 11–35.
[21] *Galli, M., Thewes, M.*: Investigations for the application of EPB shields in difficult grounds / Untersuchungen für den Einsatz von Erddruckschilden in schwierigem Baugrund). Geomechanics and Tunnelling 7 (2014), No. 1, S. 31–44.
[22] *Spagnoli G., Fernandez-Steeger T.M., Azzam R., Feinendegen M., Neher H.P., Stanjek, H.*: Investigation of adherence behaviour and related effects on different scales in mechanical tunnel driving. Proceedings of Underground Construction Prague 2010, Transport and City Tunnels (2010), S. 692–699.
[23] *Hollman, F.*: Bewertung von Boden und Fels auf Verklebungen und Feinkornfreisetzung beim maschinellen Tunnelvortrieb. PhD Thesis, Ruhr-Universität Bochum, 2014.
[24] *Jancsecz, S.*: Definition geotechnischer Parameter für den Einsatz von Schild Vortriebsmaschinen mit suspensionsgestützter Orstbrust. Forschung + Praxis 34 (1991), S. 34–60.
[25] *Alberto-Hernandez, Y., Kang, C., Yi, Y., Bayat, A.*: Clogging potential of tunnel boring machine (TBM): a review. International Journal of Geotechnical Engineering (2017), S. 1–8.
[26] *Geodata SPA.*: Review of alternative construction methods and feasibility of proposed methods for constructing Attiko Metro Extension of Line 3 to Egaleo Attiko Metro S.A., Geodata (1995), Greece.
[27] *Thewes, M, Burger, W.*: Clogging risks for TBM drives in clay. Tunnels and Tunnelling International 36 (2004), S. 28–31.
[28] *Feinendegen, M., Ziegler M., Weh, M., Spagnoli, G., Stanjek, H.*: A new laboratory test to evaluate the problem of clogging in mechanical tunnel driving with EPB-shields. Rock mechanics in civil and environmental engineering. London: Taylor Francis Group, 2010.
[29] *Zumsteg, R., Puzrin, A.M., Anagnostou, G.*: Effects of slurry on stickiness of excavated clays and clogging of equipment in fluid supported excavations. Tunnelling and Underground Space Technology 58 (2016). S. 197–208.
[30] *Zumsteg, R.*: Optimization of clay-polymer mixtures for soil conditioning. PhD Thesis, ETH Zurich, 2014.
[31] *Zumsteg, R., Plötze, M., Puzrin, A.*: Reduction of the clogging potential of clays: new chemical applications and novel quantification approaches. Géotechnique 6 (4) (2013), S. 276–286.
[32] *Peixoto da Silva, M.A.A., Katayama, L.T., Leyser, F.G., Aguiar, G., Ferreira, A.A.*: Twin tunnels excavated in mixed face conditions. ITA-WTC2017. Bergen: 2017.
[33] *Comulada, M., Maidl, U., Silva, M.A.P., Aguiar, G., Ferreira, A.*: Experiences Gained in Heterogeneous Ground Conditions at the Twin Tube EPB Shield Tunnels in São Paulo Metro Line 5. ITA-WTC2016. San Francisco, 2016.
[34] ASTM D2216-10: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, West Conshohocken, PA, 2010.
[35] ASTM D4318-17: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA, 2017.

Msc. Geol. Daniela Garroux G. de Oliveira
Herrenknecht AG
Schlehenweg 2
77963 Schwanau-Allmannsweier
Germany
garroux.daniela@herrenknecht.de

Prof. Dr. Ing. Markus Thewes
Ruhr Universität Bochum
Lehrstuhl für Tunnelbau, Leitungsbau und Baubetrieb
Universitätsstr. 150 Gebäude IC 6-129
44801 Bochum
Germany
markus.thewes@rub.de

Prof. Dr. Ing. Mark S. Diederichs
Queen´s University
Dept. of Geological Sciences and Geological Engineering
Bruce Wing 36 Union Street
K7L 3N6 Kingston, ON
Canada
diederim@queensu.ca

Ing. Lars Langmaack
Normet International Ltd
6331 Hünenberg
Switzerland
Lars.Langmaack@Normet.com

Dear authors, If possible, please provide figures 1-11 in better quality.