Clogging Assessment of Edmonton Clay

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ABSTRACT
Clogging is one of the more common phenomena closely related to the tunnelling/drilling process, and it can cause delays in a project's time schedules and lead to an economic loss. To assess clogging potential, semi-empirical and analytical approaches, and physical simulation methods are generally adopted. In this paper, the authors try to evaluate the clogging potential of Edmonton clay using an apparatus that can capture the main characteristics of tunnel boring machines (TBMs). Before the test, soil properties are investigated based on conventional geotechnical tests, including sieve analysis, Atterberg limit tests, and XRD tests. Then clogging tests are carried out, and results are analyzed. Clogging test results are also compared with the assessment results from a semi-empirical diagram proposed by other researchers to assess the clogging potential. It is indicated that results from the apparatus are consistent with that from the semi-empirical diagram. Meanwhile, the apparatus can take the drilling characteristics into consideration. Therefore, the apparatus is able to assess the degree of clogging for Edmonton clay with higher accuracy. The application of the new apparatus can be extended to evaluate the performance of conditioned soils.

1 INTRODUCTION

When a drill bit or tunnel boring machine (TBM) passes through highly sticky clays, it sometimes experiences significant clogging (Langmaack 2001; Thewes and Hollmann 2016; Wang and Yang 2015). Clogging mainly stems from adhesion that occurs in the interface of clay minerals and a metal surface (Thewes and Burge 2005; Spagnoli et al. 2011; Alberto-Hernandez et al. 2017). Clogging normally occurs on a cutting wheel, in the mixing chamber, and in the slurry line during pipeline transport (Kooistra et al. 1998). It could also lead to technical problems like high energy demand, blocking or breakdown of excavation, and economic loss, none of which are typically considered during the design process (Heuser et al. 2012; Azali et al. 2013).

The adhesion between soil particles can be classified into two parts: attraction between soil particles and a foreign object, and adhesion action between water molecules and the object (Fountaine 1954). Coarse solid particles come into contact with the metal surface by discrete rings of water. Conversely, fine soil particles stick to the metal surface through water adhesion. Jia (2004) adopted this categorization and suggested an equation to estimate the force from water ring attraction.

To understand the aspects of clogging, Kooistra et al. (1998) compared cohesion and adhesion with the shear stress applied. It is noted that if the applied stress is smaller than the shear strength at the interface but larger than the shear strength of soil, clogging occurs with a small slice of clay remaining on the metal surface. However, in the mixing chamber of the TBMs, if the applied shear stress is lower than the shear strength of soil and strength at the soil-steel interface, clogging can still be expected without internal failure of clay.

There are three approaches to study clogging potential: analytical, semi-empirical, and physical simulation (Table 1).

In analytical approaches, adhesion and cohesion are compared with the applied shear stress (Kooistra et al. 1998; Zumsteg and Puzrin 2012). Adhesion between soil and a foreign object was generally measured by pulling out the foreign object from the soil. Cohesion strength was obtained through the vane shear test.

The semi-empirical approach relies on the water content and Atterberg limits of the soil. Jancsecz et al. (1999) gathered data from a number of tunneling projects and stated that adhesion could be correlated to simple geotechnical parameters; e.g., plastic limit (*PL*), liquid limit (*LL*), and plasticity index ($PI = LL - PL$). Thewes (1999) developed a clogging potential diagram using plasticity and consistency index (I_c) based on site reports and laboratory measurements. Hollmann and Thewes (2013) updated the diagram and classified the diagram into five categories: strong clogging, medium clogging, little clogging, fines dispersing, and a lump, in which *PL*, *LL*, and initial water content were used to identify the clogging potential.

For physical simulation, the drilling process was taken into consideration in the test. Zumsteg and Puzrin (2012) employed a mixing test to determine the clogging potential of different soils. The soil remaining on the mixing tool was weighed, and a percentage of this part of the soil compared with the total weight of soil in the container was calculated. Peila et al. (2007) applied a screw conveyor that can rotate to test the properties of conditioned soil. The variation of torque force was recorded. Peila et al. (2016) updated the apparatus and changed the screw from an inclined to a vertical direction. Kang et al. (2018) developed an apparatus to simulate the drilling process with the consideration of rotational velocity, penetration rate and size of drill bit. Sensitivity analysis has been carried out on the rotational velocity, penetration rate. A new parameter was introduced to describe the clogging potential, which is the weight of soil stick to the drill bit. The apparatus has been calibrated and tested.

Soil additives are normally used to reduce clogging by modifying the soil behavior (Ball et al. 2009; Chen et al. 2017). Additives are often injected through the cutterhead or into the cutting chamber to make the muck flowable, lower the inner friction between the soil particles, control soil stickiness, and prepare the excavated soil to be compressible during tunneling operations (Langmaack

2000; Langmaack 2002). Soil additives normally used in the field are foam, polymer, and saline water. Foam is a type of mixture made from water and a surfactant (Jancsecz et al., 1999). The function of foam is to reduce the torque of the shield and decrease the necessary energy supply. Polymers have a relatively long history of use and are, for the most part, by-products from the oil drilling industry (Kupferroth et al. 2001). The function of polymers is not only to manage the face support and soil transport problem in loose, coarse soils; they can also reduce soil stickiness. Spagnoli et al. (2013 and 2014) mixed sodium chloride with soil material. Reductions of the liquid limit and undrained shear strength were detected in conditioned soil.

Table 1: Summary of existing methods used to assess the clogging potential

Approaches	Tests	Factors considered	References
Analytical approach	Vane shear test, direct shear test	Cohesion; Adhesion; Shear stress;	Kooistra et al. (1998); Zumsteg and Puzrin (2012)
Semi-empirical approach	Atterberg limit tests	Plastic limit; Liquid limit	Jancsecz et al. (1999); Thewes (1999); Hollmann and Thewes (2013)
Physical simulation	Mixing test	Rotational velocity of drill bit;	Zumsteg et al. (2013)
	Dynamic adhesion test		Peila et al. (2007); Peila et al. (2016)
	Drilling test	Rotational velocity of drill bit; Penetration rate;	Kang et al. (2018)

This paper evaluates the clogging potential of Edmonton clay using physical simulation and semi-empirical methods. The physical simulation method used in the paper is proposed by Kang et al. (2018). The universal diagram developed by Hollmann and Thewes (2013) was used to evaluate the clogging potential as well. The soil was sampled from different tunnelling sites in Edmonton. The authors also evaluate the performances of different additives using the specimens mixed with different contents of additives in clogging tests. The results from two methods are also compared.

2 METHODOLOGY

2.1 Material

In this study, Edmonton clay #1 (EC #1) and Edmonton clay #2 (EC #2) were sampled from two tunneling sites in Edmonton, which were approximately 5–6 m and 16–18 m below the ground. The initial water content of each soil was tested when the sample was taken which were 36% and 18% for EC #1 and EC#2, respectively.

Sieve analysis was carried out to obtain the particle size distribution curve of those samples, as shown in Figure 1. The hydrometer method was used for soil material finer than 0.075 mm, and the mechanical method was used for soil material larger than 0.075 mm. By observation, more than 50% of EC #1 is finer than 0.075 mm. This sample is also finer compared to the other sample.

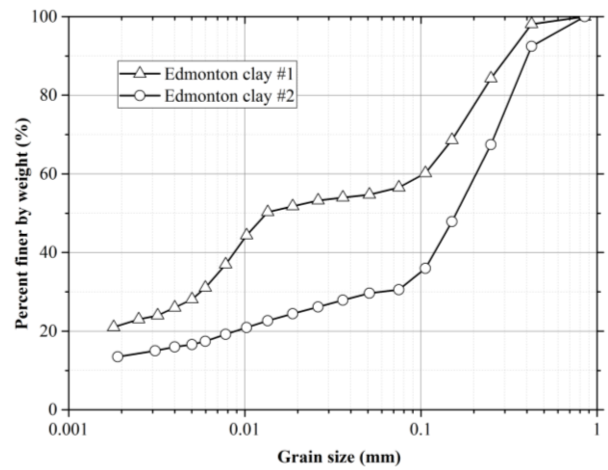

Figure 1: Particle size distribution curve for EC #1 and EC #2

Materials finer than 425 μm were used in Atterberg limit tests according to ASTM standard D4318-10. Table 2 indicates that the plasticity indexes are larger than 20%. In the tests, four to five water contents were selected between plastic limit and liquid limit with a 5% increment in water content from 25% to 45% for EC #1, and 15% to 35% for EC #2.

Table 2: Fundamental soil properties of EC #1 and EC #2

Sample #	EC #1	EC #2
Plastic limit (*PL*)	23%	16%
Liquid limit (*LL*)	47%	36%
Plasticity index (*PI*)	24%	20%
Natural water content (w_i)	36%	18%
Consistency index (I_c)	0.46	0.90
Activity index (*A*)	1.14	1.19

The mineral components in the soil can affect the soil's mechanical properties, so an X-Ray Diffraction (XRD) test was conducted to understand the mineralogical components in the soil before performing the clogging tests, as shown in Figure 2. The results indicate that the main mineralogical components in the soil are quartz, kaolinite, and illite for all three samples, showing that the mineralogical components are very similar.

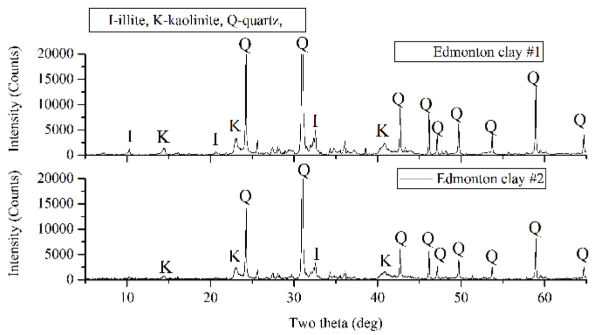

Figure 2: XRD test results of EC#1 and EC#2

In this test, two different soil additives, including clay cutter and soap, are mixed with EC #1 under different water contents. Clay cutter liquid is a type of polymer that is often used as an additive for horizontal directional drilling (HDD) bores in reactive clay soils. Soap solution is another type of solution that can be used to change the consistency of the clay. It appears as a brown solution without an irritant odour. The specific gravity is 1.08 and PH is 7.5.

2.2 Testing apparatus and procedures

Two types of testing were carried out, including Atterberg limit tests and clogging drilling tests. The Atteberg limits of the soil were tested under ASTM standard D4318-10. The three-point method was adopted to determine the liquid limit. To prepare conditioned soil for *PL* and *LL* tests, the soil was first mixed with the desired content of additives. The conditioned soil was then dried, crushed and sieved, and *PL* and *LL* were tested.

The apparatus developed by Kang et al. (2018) is composed of four main parts: power supply, motor, controller, and drill bit. The power supply provides the driving force for this apparatus and the motor converts the supplied power into the driving force. A penetration controller regulates the advance rate, and a ruler is used to limit the penetration depth. Penetration speed is calculated by dividing the penetration depth by the time taken for the penetration process. The drill consists of a drill bit and a steel mould. The drill bit is removable, and different sizes of drill bits can be installed. The drill bits were manufactured to US standard, and the size of the drill bit used in the tests was 3 in (76.20 mm). In the test, centrifugal force at the boundary of the drill bit was considered the same as that of a TBM. According to the rotational velocity and the diameter of a TBM working in one of the tunnels in South Edmonton, the corresponding rotational velocity that should be used was 30 rpm.

After the drill bit carefully made contact with the soil sample through adjusting the height of the base, the drill bit was pushed downward under an expected speed until reaching the desired depth. Then, the drill bit was pulled out from the soil sample and the machine was switched off. The soil mass remaining on the drill bit was weighed once the soil above the top surface of the drill bit was removed since this part had passed the drill bit and therefore cannot be considered as clogged material.

When additives are involved, the sample preparation process for testing the soil mixed with additives is not completely the same as that for plain soils. Additives are mixed with distilled water first. As a result, instead of mixing the soil with water during the mixing process, the solution composed of distilled water and one type of additive is mixed with the soil grind. Then the mixed liquid was used in soil preparation following the same procedure as mentioned above.

3 TEST RESULTS AND ANALYSIS

3.1 Test results of plain soils

Figure 3 shows the results for the soil samples. The maximum *WSDB* for EC #1 and EC #2 is 5.69 kg/m^2 and 6.04 kg/m^2, respectively. Overall, *WSDB* increases from *PL* and reaches a peak value before the water content reaches *LL*. Then, the *WSDB* drops before it reaches *LL*. The *WSDB* reaches the peak values when I_c is 0.5 for EC #1 and when I_c is 0.3 for EC #2. Clogging is detected when I_c is smaller than 1.

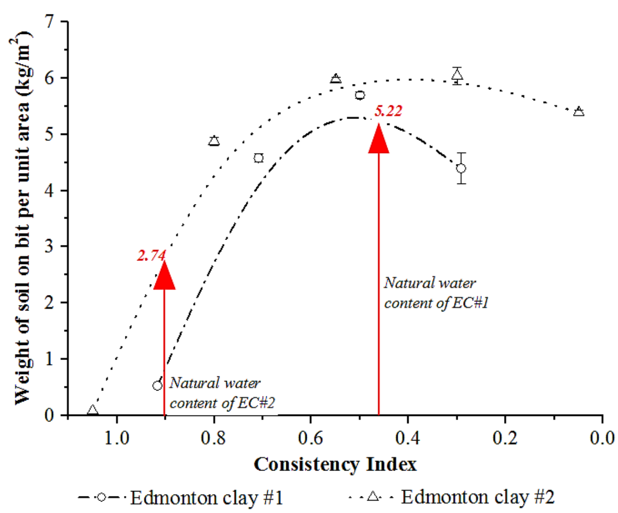

Figure 3: Clogging test results for different plain soils with natural water content labeled

The WSDB for EC #1 and #2 under the initial water contents, interpolated from Figure 3 is 5.22 kg/m^2 and 2.74 kg/m^2, respectively. For EC #1, the *WSDB* at its initial water content is close to the maximum *WSDB*. Although *WSDB* of EC #2 does not reach the maximum value, clogging is still observed. When sampling EC #2, the TBM can continue working; however, soil easily stuck to the band of the conveyor, which means that the results are in agreement with field situations.

Based on the diagram developed by Thewes (1999), Hollmann and Thewes (2013) extended the diagram to all TBM open modes, which can be used to differentiate the clogging potential under different water contents according to the *PL* and *LL* of the soil (Figure 4). Water content increases by 5% for each soil. For EC #1 the investigated consistencies were between 0.92 and 0.29, and for EC #2, between 1.05 and 0.05. Figure 4 indicates that strong clogging generally occurs when I_c is between 0.50 and 0.75.

From the drilling apparatus, the maximum values of *WSDB* for each soil are detected when the I_c is 0.51 and 0.54. This suggests that when using the drilling apparatus, strong clogging occurs when the water content is close to *LL*. Figure 4 also indicates that the width of the strong clogging area decreases from EC #1 to EC #2, meaning that clogging potential decreases.

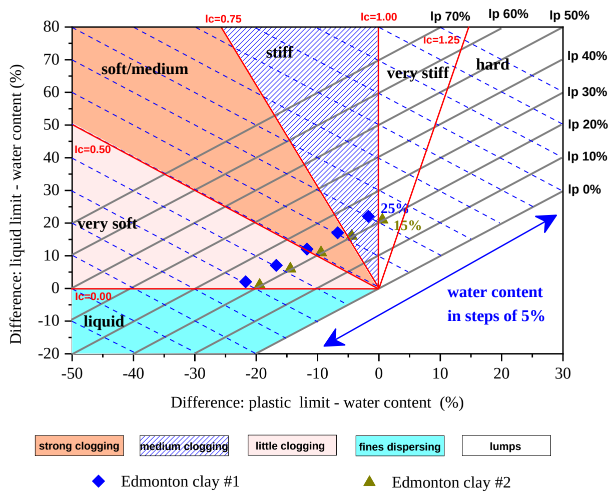

Figure 4: Plot of clogging results tested using the new apparatus on a universal diagram proposed by Hollmann & Thewes (2013)

3.2 Test results of conditioned soil

Figure 5 shows the results as a percentage of WSDB with and without additives. When I_c = 0.71, as shown in Figure 5(a), the relative degree of clogging (*RDC*) for clay cutter is 65% on average. The *RDC* of soap is also smaller than 100% (Figure 5(b)), but larger than that of clay cutter. When I_c = 0.5, the *RDC* decreases for all of them. However, the *RDC* of clay cutter still decreases faster than that of soap. When I_c decreases to 0.29, the *RDC* of soap and clay cutter are very close to each other. Overall, both indicate they have an effect on the reduction of clogging. However, this effect decreases with the increase of original water content. When more water is involved, it means that the content of additives is diluted, showing that the effect of additives decreases.

The performances of different additives were also assessed using the clogging assessment diagram, stickiness ratio, and the variation of plastic limit. All of these diagrams were developed to assess plain soil. In this paper, they were creatively used to assess the clogging potential of the conditioned soil.

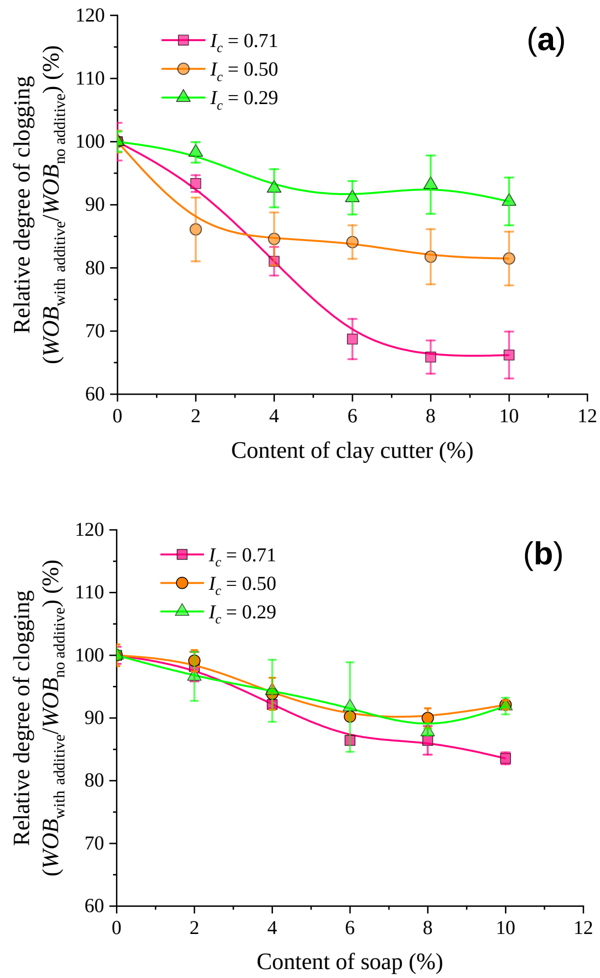

Figure 5: RDC for conditioned soils for (a) clay cutter and (b) soap

Figure 6 indicates the variation of clogging potential after adding different contents of additives based on the universal diagram proposed by Hollmann and Thewes (2013). In the figures, hollow symbols represent the soil without additives, and solid symbols represent the soil with additives. The size of the symbols shows the content of additives in the soil. In Figure 6, each increment of symbol size means a 2% increase of an additive in the soil.

Figure 6(a) demonstrates the performance of clay cutter. When the content of additives increases, the points indicating clogging potential move towards the region with a smaller plasticity index, showing lower clogging potential or no clogging when the additive content is 10% for soil with 30% water content. The effectiveness of soap is not apparent. For a water content of 30%, it seems that soap could reduce the clogging potential. However, when the water content is 35% or 40%, it is difficult to detect clogging reduction by increasing the content of additive.

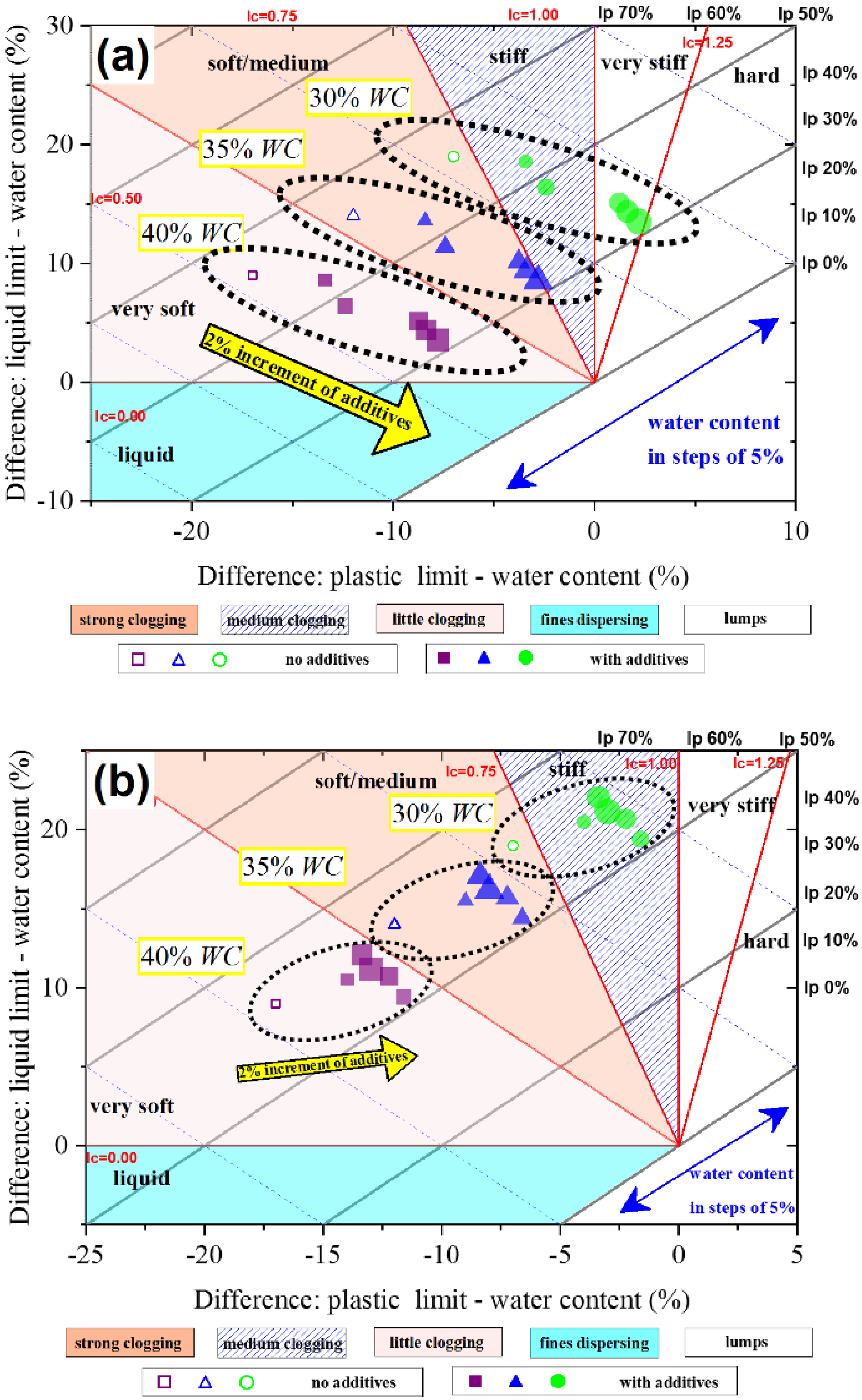

Figure 6: Performance of soil additives evaluated using semi-empirical diagram (a) clay cutter and (b) soap

4 CONCLUSIONS

The clogging test revealed that the WSDBs for soil under the initial water contents are 5.22 kg/m^2 and 2.74 kg/m^2. The maximum *WSDB* for EC #1 and EC #2 is 5.69 kg/m^2 and 6.04 kg/m^2, respectively. The semi-empirical diagram indicates that strong clogging generally occurs when I_c is between 0.50 and 0.75. From the drilling apparatus, the maximum values of *WSDB* for each soil are detected when the I_c is 0.51 and 0.54.

The apparatus overall indicates similar results as the semi-empirical diagram proposed by Hollmann and Thewes (2013); however, the apparatus can clearly show the weight of soil that could stick to the TBM machine, rather than simply indicate the clogging potential.

The clogging potential of additive soils reveals that clay cutter is a more effective additive compared to soap. With the decrease of I_c from 0.71 to 0.29, the difference of *RDC* decreases from 20% to almost 0%.

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