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1 **Assessment of the clogging potential of two clays**

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Abstract: Clogging sometimes occurs in tunnelling projects. Soils containing high plasticity clay minerals have a high potential for clogging. To gain a better understanding of the effect of swelling clay on the clogging potential, two different clays, bentonite and kaolin, were tested in different proportions. Several approaches were employed to evaluate clogging potential, including a semi-empirical diagram, laboratory-based drilling tests, and evaluation of the variation of the plasticity indexes. The performance of an additive was also evaluated using the same method as for pure mixtures. To determine the correlation between the mechanical properties and clogging potential of the mixtures, vane shear tests were carried out on the mixtures containing the additive. The results revealed that mixtures with bentonite had a higher clogging potential than pure kaolin. The performance of additives used for mitigation of clogging also changed with the content of bentonite in the mixtures. The simple drilling tests were capable of quantitatively differentiating the clogging potential of plain mixtures and evaluating the performance of additives.

Keywords: montmorillonite, kaolinite, additive, clogging potential, vane shear test

1. INTRODUCTION

Clogging is a phenomenon that occurs because cohesive materials tend to adhere to cutting tools at the cutterhead, openings of the cutterhead, screw conveyor, or conveyor belt. This, in turn, can lead to severe problems in tunnelling projects, including excavation difficulties, an extension of the project timetable and, consequently, budget overrun (Thewes, 1999; Spagnoli et al., 2014; Thewes and Hollmann, 2014; Zumsteg et al., 2016; Oliveira, 2018). Clogging is a result of the attraction between soil particles and a foreign object, as well as adhesion between water in the soil and the object (Fountaine, 1954; Lal and Shukla, 2004; Zhang et al., 2018). Thewes (1999) and Jia (2004) classified the mechanism of adhesion of clay to a steel surface into four single mechanisms: adhesion of clay particles on a component surface, inherent cohesion, bridging of clay particles over an opening, and the low tendency of clay to dissolve in water. In an attempt to understand the mechanism of clogging, different approaches have been used, including analytical approaches, semi-empirical approaches, and physical simulation (Table 1).

Foam and polymers have generally been adopted to lower the clogging potential in tunnelling projects (Jancsecz et al., 1999; Quebaud et al., 1998; Blanck et al., 2014; Zumsteg et al., 2016). However, the performance of foam additives used with clay is not as beneficial as when they are used with sand. Therefore, most of the time, water is used to mitigate clogging in clayey soil by decreasing the consistency index (I_c). Kang et al. (2018) used a clay cutter (CC) as an additive in clogging tests, which was later adopted by the City of Edmonton to mitigate clogging for some tunneling projects. The performance of the additives was evaluated using the semi-empirical diagram proposed by Hollmann and Thewes (2013) and the drilling test.

The presence of bentonite in the soil can result in a high potential for clogging, resulting from swelling of the montmorillonite. Although the effect of bentonite on Atterberg limits has been

tested (Sivapullaiah and Sridharan, 1985; Polidori, 2007), the degree of clogging has not been assessed with the rate of penetration being considered: moreover, the effect of bentonite on clogging potential has not been studied quantitatively using a drilling test. Kaolin is a type of non-swelling clay, although soil with kaolin can still cause clogging (Hollmann and Thewes, 2013; Oliveira, 2018). For this reason, bentonite was mixed with kaolin in different proportions to study the effect of bentonite on clogging potential using a drilling test, and the results were compared in a semi-empirical diagram. Different concentrations of an additive were also mixed with bentonite-kaolin mixtures to study the influence of bentonite content on the performance of the additive. The authors also investigated the difference in clogging potential in relation to the mechanical properties of the mixtures.

2. TESTING APPARATUS AND METHODS

The soil mixtures used in the tests contained different percentages of sodium bentonite (AQUAGEL GOLD SEAL) and kaolin (EP Kaolin), identified as M^0 , M^{20} , M^{40} , M^{60} , M^{80} , and M^{100} (Table 2), with the superscript indicating the percentage of bentonite in the mixture. X-ray diffraction revealed that the major mineralogical component of the kaolin used in this study was kaolinite. Minor phases such as quartz and gypsum were also present. The major mineral in the sodium bentonite was montmorillonite. There were small amounts of quartz and gypsum in the bentonite as well.

Before each of the drilling tests, dry bentonite and kaolin powders were mixed together by weight, and the desired amount of water was added. The samples were placed in a moisture room for at least 24 hours to allow the water to redistribute. In the tests, a concentrated polymer solution, referred to as CC, was used as the additive. The appearance of the CC was clear to amber liquid. The CC lowered pullback force and torque, and it previously demonstrated good

performance in mitigating clogging (Kang et al., 2018). In the tests with additives, the additive solution, together with the amount of water needed to reach the specified moisture content, was added to the powdered mixture of bentonite and kaolin. The content of additive in the mixture varied from 0% to 10%, in increments of 2%. The rest of the procedure was the same as described for pure kaolin-bentonite mixtures. The cation exchange capacity (CEC) of the mixtures and specific surface area (SSA) were also tested according to Cokca and Birand (1993) and Petersen et al. (1996), respectively. Table 2 summarizes the properties of the mixtures. An apparatus was developed as a simple tool to assess the clogging potential (Kang et al., 2018). This apparatus allowed the effect of penetration rate and rotational speed to be controlled during the tests. To give comparable results, the Atterberg limits of the mixtures were measured and plotted on the semi-empirical diagram proposed by Hollmann and Thewes (2013). The mechanical properties of soil were helpful in understanding the variation in clogging potential, thus, the vane shear test was also conducted on the soil mixtures. Both the clogging test and vane shear test were repeated at least three times on replicate samples, and the average values were used for the analysis. The clogging test apparatus consisted of a drill and a controller (Figure 1). The apparatus was sensitive to penetration speed and rotational velocity (Kang et al., 2018). Comparison of the test results with the observed clogged soil in drilling process showed that the clogging assessment results agreed with results observed in the field, although drilling was performed vertically in the test instead of horizontally. During the test, the rotating drill bit was pushed down with a constant, controlled speed until the desired depth was reached. The drilling bit was then pulled out, and mass of the soil remaining on the drill bit was weighed to calculate the weight of soil on the drill bit per unit area (*WSDB*). In the test, the diameter of the drill bit was 76.20 mm, and the

soil mixture was placed in a standard mold and compacted according to ASTM standard D1557. A controller was used to set the penetration speed, penetration depth, and rotational velocity. The penetration speed and rotational velocities used were 1 mm/s and 30 rpm, respectively. The penetration depth was 1 cm. The parameter used to describe the clogging potential was *WSDB*, which was calculated by dividing the weight of soil clinging to the bit by the cross-sectional area of the drill bit.

The Atterberg limits of the soil mixture were tested under ASTM standard D4318-10. In the liquid limit test, the three-point method was adopted. The conditioned mixtures were sampled after the drilling test to obtain the Atterberg limits. Samples were dried, crushed, and sieved using sieve #40.

A simple vane shear apparatus was used to measure the shear strength of the mixtures following ASTM standard D4648M-16 (2016). The diameter and height of the shear vane used in the tests were 12.7 mm and 12.7 mm, respectively. Samples were prepared with desired water and additive contents and compacted with the standard proctor method. The shear strength was calculated according to the maximum torque on the shear vane applied by the soil close to the cylindrical shearing surface.

Table 3 shows the water content of the samples used in the drilling tests. The consistency index corresponding to the water content of each of the mixtures was calculated according to $I_c = (LL - w)/(LL - PL)$, in which *LL* is the liquid limit, *w* is the water content, and *PL* is the plastic limit.

Five samples with different water contents distributed evenly between *PL* and *LL* were used for each mixture. For each composition of kaolin and bentonite (i.e. M^0 , M^{20} , M^{40} , M^{60} , M^{80} , and M^{100}), the sample with the water content that gave the highest clogging potential was chosen to

evaluate the performance of the additive. Different amounts of the additive were added, and the samples were tested using the clogging test and vane shear test.

3. LABORATORY RESULTS

3.1. Plain mixtures

Table 4 shows the variation of the degree of clogging for different mixtures. The *WSDB* increased with decreasing I_c , as a result of the increase of moisture content in the mixtures. After reaching a maximum value, *WSDB* decreased. *WSDB* reached the maximum values when the consistency indices, I_c , were in the range of 0.4 to 0.7.

It was known that increasing the content of bentonite can lead to a variation in the *PLs* and *LLs* of the soil. Figure 2 indicates that increasing bentonite content in the mixtures led to an increase in the plasticity index (I_p), indicating a higher potential of clogging according to the empirical diagram. Additionally, Figure 2 shows that the mixtures were more sensitive to water when the content of bentonite was lower, since the I_p lines of the mixture became shorter in each potential clogging zone. The plasticity index, I_p , increased with the variation of the mixture, which was another parameter used to indicate the clogging potential. Essentially, the variation of I_p with respect to bentonite content gave the same information shown in Figure 2, since they all stemmed from Atterberg limits.

3.2. Conditioned soils

The performance of the additive was evaluated using the results from both the clogging apparatus and the empirical diagram. Table 5 indicates the percentage of average reduction in *WSDB* for each mixture containing different contents of CC.

According to the Atterberg limit results, the clogging potential of the mixtures was also assessed using a semi-empirical diagram (Figure 3). The water content (hollow symbols) corresponded to

the largest clogging potential for each mixture tested in Figure 2. For M^0 , when CC was added (large symbols), the mixtures had a lower potential for clogging. However, if bentonite was involved, the points fell into the “very soft” and “liquid” zones. This agreed with the results observed during the mixture preparation process. However, when the clogging tests were carried out, the results were similar to those shown in Table 5.

3.3. Vane shear test

Vane shear tests were carried out on M^0 at the water content resulting in the maximum value of *WSDB*. In addition, mixtures conditioned with different CC contents were also tested. The mixtures reached the maximum value of *WSDB* at approximately the same value of I_c ; however, since the Atterberg limits varied between the samples, the moisture contents of the mixtures with the largest value of *WSDB* were quite different.

Table 6 shows the variation of shear strength of the mixtures conditioned with different CC content. Different percentages of additive in the conditioned mixtures resulted in different Atterberg limits, although the initial moisture content of M^0 was the same. Therefore, the variation of the shear strength was likely due to the change of the consistency index of the conditioned mixtures. For mixtures containing bentonite, the shear strength decreased with an increasing percentage of CC in the mixture. Thus, mixtures with and without CC added were shown to exhibit different shear strength behaviour.

4. DISCUSSION

4.1. Plain mixture

When the content of bentonite was increased, the maximum value of *WSDB* increased, then gradually dropped (Figure 4a). This showed that including bentonite content resulted in an increase in clogging potential. When more than 20% bentonite was involved, the maximum

WSDB started to decrease; however, the maximum WSDB of pure bentonite, M^{100} , was still larger than M^0 . According to the semi-empirical diagram, mixtures with a maximum clogging potential were always in the strong clogging zone (Figure 4b). However, the difference in the clogging potential was not identified.

A decrease in shear strength of the mixtures with increasing bentonite content was observed for maximum clogging potential. This decrease in the shear strength was probably due to increased water content in the mixtures. Although the I_c values in Figure 4b were close to each other, the water content in each of the mixtures was quite different, since PL and I_p increased.

The maximum clogging potential was found to not only be related to one soil property (i.e. Atterberg limit, shear strength, etc.). Instead, it depended on multiple soil properties. This was to be expected since the maximum clogging potential resulted from a combination of adhesion between the particles in the mixture and foreign material, and interactions between water and the same foreign material. When bentonite was involved, the adhesion between the particles in the mixture and foreign material increased, which caused an increase in the clogging potential, although an increase in water content led to a decrease in the adhesion force between the water film and the steel surface. However, when more bentonite is added to the mixtures, the increase of the adhesion force between the particles in the mixture and the steel surface was offset by a reduction in adhesion between the water film and steel surface. This reduction was even larger than the force between the particles in the mixture and steel surface, leading to a decrease in the clogging potential.

4.2. Conditioned mixtures

Since bentonite particles have large specific surface areas, the clogging potential of mixtures containing bentonite was different from pure kaolin. For M^0 , the mixture with 40% water content reached maximum clogging. Therefore, when the water content of the mixtures varied, WSDB decreased. The PL and LL increased when 2% CC were used (Figure 5a). Additionally, the

plasticity index of pure kaolin with 2% CC, I_p , increased, as shown in Figure 5. The initial water content, 40%, was less than the PL , which resulted in an increase in soil strength and a decrease in $WSDB$. However, when PL increased and LL decreased with continued increasing CC content, the water content was below the plastic limit. The mixture became drier, which resulted in an increase in the shear strength in the mixture and a decrease of the interface shear strength. Therefore, this resulted in a lower $WSDB$. As more CC was involved, the liquid in the additive increased the moisture content of the mixtures. Therefore, the $WSDB$ of the mixture increased. In summary, the variation in $WSDB$ observed was a result of changes in Atterberg limits and water content.

However, for mixtures with bentonite contents less than 50%, the PL overall increased and the LL decreased. While the variation of $WSDB$ showed the same trend, $WSDB$ decreased overall, which is the same as the results in Table 5. For mixtures with bentonite contents larger than 50%, the explanation behind the changes observed is the same. Mixtures with and without bentonite showed different performance in the simple drilling test used to measure clogging assessment. This was possibly due to the crystalline structure of bentonite, and the potential for exchangeable cations to hydrate, resulting in a significant change of the Atterberg limits of the mixtures that, together with the high water content, concealed the effect of the additive.

4.3. Performance of the clogging test and semi-empirical diagram

For plain mixtures, the semi-empirical diagram showed the overall clogging potential of the mixtures indicated by the change of the “clogging path” in the clogging zones. In comparison, the relationship between $WSDB$ and water content provided a practical, quantitative measure of the quantity of material sticking to the drill bit. The semi-empirical diagram cannot be used to describe the clogging potential of conditioned mixtures since it was not initially developed for

conditioned soil. The clogging test could be used to indicate the degree of clogging for mixtures with and without additives, which provided a useful initial assessment of clogging potential.

5. CONCLUSIONS

This paper presented the results of a clogging potential assessment of mixtures composed of two different clays, bentonite and kaolin, in different proportions from 0% (M^0) to 100% (M^{100}) in increments of 20%. The letter M denotes mixture, and 0 or 100 denotes the percentage of bentonite in the mixtures. A concentrated polymer solution, referred to as CC, was used as an additive to study its effect in the observed clogging potential of the mixtures. The testing apparatus previously developed had the ability to control the rotational velocity and penetration rate. The indices used to assess the clogging potential included the weight of soil on the drill bit per unit area ($WSDb$) per unit area remaining after the test corresponding to different values of the consistency index (I_c). The results of these tests were also evaluated and compared with the semi-empirical diagram developed by Hollmann and Thewes (2013).

The maximum clogging potential was detected when I_c was approximately 0.6 for plain mixtures. The maximum value of $WSDb$ for each mixture reached a peak value when the content of sodium bentonite was approximately 20%, and then started to decrease. One possible explanation was that when more bentonite was added to the mixture, the increase of the adhesion force between the particles in the mixture and the steel surface was offset by a reduction in adhesion between the water film and steel surface. This reduction was even larger than the force between the particles in the mixture and steel surface, leading to a decrease in the clogging potential.

The addition of a concentrated polymer solution led to a decrease in Atterberg limits, which further affected the soil strength. $WSDb$ dropped to a minimum value when 4% CC was used for

234 M^0 . For mixtures containing bentonite, an increase in bentonite content (<50%) resulted in a
235 decrease of the corresponding *WSDB*. However, for mixtures containing more than 50%
236 bentonite, the reduction in *WSDB* with increasing bentonite content was not as obvious. This was
237 possibly due to the crystalline structure of montmorillonite, and the potential for exchangeable
238 cations to hydrate, resulting in a significant change of the Atterberg limits of the mixtures that,
239 together with the high water content, concealed the effect of the additive.

240 Compared with the semi-empirical diagram introduced by Hollmann and Thewes (2013), the
241 results of drilling tests give a quantitative measure of the degree of clogging potential for
242 unmodified mixtures and mixtures conditioned with the additive. Therefore, the simple drilling
243 test described in this work could be used to assess the clogging potential of different soils and
244 evaluate the performance of different additives.

245 **Declarations of interest: none**

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REFERENCES

- Alberto-Hernandez, Y., Kang, C., Yi, Y. L., and Bayat, A., 2018. Mechanical properties of clayey soil relevant for clogging potential. *International Journal of Geotechnical Engineering*, 12(6), 529-536.
- ASTM D1557-12, 2012. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³)), *ASTM International*, West Conshohocken, PA, DOI: 10.1520/D1557-12.
- ASTM D4318-10., 2010. Standard test methods for liquid limit, plastic limit, and plasticity index of soils, *ASTM International*, West Conshohocken, PA, DOI: 10.1520/D4318.
- ASTM D4648M-16., 2016. Standard test methods for laboratory miniature vane shear test for saturated fine-grained clayey soil, *ASTM International*, West Conshohocken, PA, DOI: 10.1520/D4648_D4648M-16.
- Blanck, G., Cuisinier, O., and Masrouri, F., 2014. Soil treatment with organic non-traditional additives for the improvement of earthworks. *Acta Geotechnica*, 9(6), 1111-1122.
- Cokca, E. and Birand, A., 1993. Determination of cation exchange capacity of clayey soils by the methylene blue test. *Geotechnical Testing Journal*, 16(4), 518-524.
- Fontaine, E., 1954. Investigations into the mechanism of soil adhesion. *Journal of Soil Science*, 5(2), 251-263.
- Hollmann, F. and Thewes, M., 2013. Assessment method for clay clogging and disintegration of fines in mechanised tunnelling. *Tunnelling and Underground Space Technology*, 37, 96-106.

272 Jancsecz, S., Krause, R., and Langmaack, L., 1999. Advantages of soil conditioning in shield
 273 tunnelling: experiences of LRTS Izmir. Challenges for the 21st Century, Alten et al. (eds),
 274 pp. 865-875.

275 Jia, X., 2004. Theoretical analysis of the adhesion force of soil to solid materials. *Biosystems*
 276 *engineering*, 87(4), 489-493.

277 Kang, C., Yi, Y. L. and Bayat, A., 2018. Laboratory test of assessing TBM clogging potential
 278 and evaluating the performance of additives. *International Journal of Geotechnical*
 279 *Engineering*, DOI: 10.1080/19386362.2018.1439671.

280 Lal, R. and Shukla, M. K., 2004. Principles of soil physics: CRC Press.

281 Littleton, I., 1976. An experimental study of the adhesion between clay and steel. *Journal of*
 282 *Terramechanics*, 13(3), 141-152.

283 Oliveira, D., 2018. EPB excavation and conditioning of cohesive mixed soils: clogging and flow
 284 evaluation. Ph.D. thesis, Queen's University, Kingston, Canada. 2018.

285 Peila, D., Picchio, A., Martinelli, D., and Dal Negro, E., 2016. Laboratory tests on soil
 286 conditioning of clayey soil. *Acta Geotechnica*, 11(5), 1061-1074.

287 Petersen, L. W., Moldrup, P., Jacobsen, O. H., and Rolston, D. E., 1996. Relations between
 288 specific surface area and soil physical and chemical properties. *Soil Science*, 161(1), 9-21.

289 Polidori, E., 2007. Relationship between the Atterberg limits and clay content. *Soils and*
 290 *foundations*, 47(5), 887-896.

291 Quebaud, S., Sibai, M., and Henry, J.P., 1998. Use of chemical foam for improvements in
 292 drilling by earth-pressure balanced shields in granular soils. *Tunnelling and Underground*
 293 *Space Technology*, 13(2), 173-180.

294 Sivapullaiah, P. and Sridharan. A., 1985. Liquid limit of soil mixtures. *Geotechnical Testing*
295 *Journal*, 8(3), 111-116.

296 Spagnoli, G., Stanjek, H., Feinendegen, M., and Azzam, R., 2014. Mineralogical, mechanical
297 and electrical properties of the clays and their relation with regard to the clogging during
298 mechanical tunnel driving. *Geo-characterization and Modeling for Sustainability*, 495-504.

299 Thewes, M., 1999. Adhäsion von Tonböden beim Tunnelvortrieb mit Flüssigkeitsschilden,"
300 Institut für Bodenmechanik und Grundbau, Gesamthoch, Ph.D. thesis, Bergische
301 Universität Wuppertal, Aachen, Germany. 1999.

302 Thewes, M. and Hollmann, F., 2014. TBM-specific testing scheme to assess the clogging
303 tendency of rock. *Geomechanics and Tunnelling*, 7(5), 520-527.

304 Zhang, F. Y., Kong, R., and Peng, J. B., 2018 Effects of heating on compositional, structural, and
305 physicochemical properties of loess under laboratory conditions, *Applied Clay Science*,
306 152, 259-266.

307 Zumsteg, R., Plötze, M., and Puzrin, A., 2013. Reduction of the clogging potential of clays: new
308 chemical applications and novel quantification approaches. *Geotechnique*, 63(4), 276-286.

309 Zumsteg, R., Puzrin, A. M., and Anagnostou, G., 2016. Effects of slurry on stickiness of
310 excavated clays and clogging of equipment in fluid supported excavations. *Tunnelling and*
311 *Underground Space Technology*, 58, 197-208.

312 *Table 1: Summary of tests to investigating clogging potential and the main factors considered*
313 *revised from Kang et al. (2018))*

Approaches	Indices used to assess clogging	Tests	Factors considered	Units	References
Analytical approach	Compare the adhesion and cohesion with shear stress	Vane shear test, direct shear test;	Cohesion, adhesion, and shear stress	N/A	Littleton (1976); Alberto-Hernandez et al. (2018);
Semi-empirical approach	Plastic limit, liquid limit, water content	Atterberg limit tests	Plastic limit and liquid limit	N/A	Jancsecz et al. (1999); Thewes (1999); Hollmann and Thewes (2013);
Physical simulation	Weight of soil stick to the drill bit	Mixing test	Rotational velocity	kg or %	Zumsteg et al. (2013); Oliveira (2018);
	Torque force	Dynamic adhesion test	of drill bit	kN	Peila et al. (2016)
	Weight of soil stick to the drill bit in unit area	Drilling test	Rotational velocity, penetration rate and size of drill bit.	kg/m ²	Kang et al. (2018)

Table 2: Composition of the mixtures used and their corresponding physical properties measured in the laboratory (SSA stands for the specific surface area; MBV is methylene blue value; CEC denotes cation exchange capacity)

Mixture #	M ⁰	M ²⁰	M ⁴⁰	M ⁶⁰	M ⁸⁰	M ¹⁰⁰
Bentonite (%)	0	20	40	60	80	100
Kaolin (%)	100	80	60	40	20	0
Plastic limit (%)	33	36	38	40	42	44
Liquid limit (%)	56	128	189	260	338	392
SSA (m ² /g)	82	121	328	433	774	988
MBV (g/100g)	3.4	4.9	13.4	17.7	31.6	40.4
CEC (meq/100g)	11	15	42	55	99	126

318 *Table 3: Water content (w) and corresponding consistency index (I_c) of samples used in the*
319 *drilling tests (*samples used in the vane shear tests and as a basic mixture to evaluate the*
320 *performance of the additive). These samples were selected since they exhibited the relative*
321 *maximum clogging potential based on the semi-empirical diagram and in the drilling tests.*

Sample	#1		#2		#3		#4		#5	
Tested	w (%)	I_c	w (%)	I_c	w (%)	I_c	w (%)	I_c	w (%)	I_c
M⁰	30	1.12	35	0.90	40 [*]	0.68	45	0.47	50	0.25
M²⁰	30	1.06	50	0.85	70 [*]	0.63	90	0.41	110	0.19
M⁴⁰	40	0.99	70	0.79	100 [*]	0.59	130	0.39	160	0.19
M⁶⁰	45	0.98	95	0.75	145 [*]	0.52	195	0.30	245	0.07
M⁸⁰	50	0.97	110	0.77	170 [*]	0.57	230	0.36	290	0.16
M¹⁰⁰	50	0.98	120	0.78	190 [*]	0.58	260	0.38	330	0.18

322 *Table 4: Clogging assessment of the mixtures with different amounts of bentonite at the*
323 *corresponding consistency index (I_c). The weight of soil on the drill bit per unit area (WSDB)*
324 *together with the error in the tests (Err) were included.*

I_c	M^0 (kg/m ²)		I_c	M^{20} (kg/m ²)		I_c	M^{40} (kg/m ²)		I_c	M^{60} (kg/m ²)		I_c	M^{80} (kg/m ²)		I_c	M^{100} (kg/m ²)	
	WSDB	Err		WSDB	Err		WSDB	Err		WSDB	Err		WSDB	Err		WSDB	Err
1.12	0.0	0.1	1.06	0.8	0.1	0.99	3.3	0.4	0.98	3.3	0.3	0.97	3.9	0.4	0.98	3.3	0.4
0.90	2.3	0.3	0.85	5.5	0.9	0.79	6.2	0.7	0.75	5.6	0.2	0.77	4.9	0.5	0.78	4.3	0.4
0.68	4.5	0.1	0.63	6.7	0.1	0.59	6.7	0.5	0.52	5.9	0.5	0.57	5.6	0.8	0.58	5.5	0.5
0.47	4.7	0.5	0.41	6.9	0.6	0.39	6.4	0.2	0.30	5.6	1.1	0.36	5.4	0.0	0.38	4.8	0.8
0.25	4.3	0.48	0.19	6.4	0.6	0.19	6.4	0.7	0.07	4.9	1.6	0.16	4.9	0.2	0.18	4.6	0.4

325

326 *Table 5: Relative clogging degree of the mixtures for different amounts of additive (Err stands*
327 *for error in the tests)*

Additive %	M^0 (%)		M^{20} (%)		M^{40} (%)		M^{60} (%)		M^{80} (%)		M^{100} (%)	
	Relative clogging	Err	Relative clogging	Err	Relative clogging	Err	Relative clogging	Err	Relative clogging	Err	Relative clogging	Err
0%	100	6	100	5	100	6	100	8	100	1	100	1
2%	83	4	89	3	97	5	106	3	111	7	103	2
4%	70	1	80	4	88	8	105	3	108	7	104	2
6%	81	6	75	9	79	16	103	9	105	12	104	5
8%	83	5	69	1	79	3	101	15	95	15	104	12
10%	99	6	68	11	76	6	94	14	92	16	102	16

Table 6: Shear strength of the mixtures containing different amounts of CC (kPa)

Additive %	M⁰	M²⁰	M⁴⁰	M⁶⁰	M⁸⁰	M¹⁰⁰
0%	26	8	6	5	6.	6
2%	64	5	4	4	5	4
4%	51	3	3	2	4	3
6%	31	1	1	2	3	3
8%	25	1	1	1	2	3
10%	22	1	1	1	1	1

330 *Figure 1: A Schematic diagram of clogging assessment apparatus. V is the penetration rate*
331 *(mm/s) and N is the rotational velocity (rpm). The figure on the right hand size is a magnified*
332 *view of the drilling bit. The parameter m_c is the weight of soil on the drill bit and A_c is the cross-*
333 *sectional area of drill bit. The weight of soil on drill bit per unit area (WSDB) is equal to $m_c /$*
334 *A_c .*

335 *Figure 2: Clogging assessment of plain mixtures using the universal diagram proposed by*
336 *Hollmann and Thewes (2013).*

337 *Figure 3: Clogging potential assessment of the conditioned mixtures using the diagram proposed*
338 *by Hollmann and Thewes (2013). Each mixture without additive has the highest clogging*
339 *potential when different amounts of water were added according to drilling tests in the previous*
340 *study. For each mixture, the sample with highest clogging potential was used to study the effect*
341 *of the additive on the clogging indicated as hollow symbols in the figure.*

342 *Figure 4: Properties of mixtures with different content of bentonite at the maximum clogging*
343 *potential in this study (a) maximum clogging potential of each mixture, (b) consistency index,*
344 *and (c) shear strength.*

345 *Figure 5: Correlation between the clogging potential and mixture properties for M^0 with CC. (a)*
346 *Atterberg limits of M^0 with CC, (b) shear strength of the M^0 , and (c) WSDB of M^0 .*

Highlights:

- 1 Two approaches were employed to evaluate the clogging potential of two clays
- 2 Maximum clogging potential was observed for plain mixture with 20% bentonite
- 3 Conditioned mixtures with and without bentonite showed different clogging potential
- 4 Drilling tests can quantitatively differentiate clogging potential of mixtures

Figure 1

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Figure 1: Schematic diagram of clogging assessment apparatus. V is the penetration rate (mm/s) and N is the rotational velocity (rpm). The figure on the right hand side is a magnified view of the drilling bit. The parameter m_c is the weight of soil on the drill bit and A_c is the cross-sectional area of drill bit. The weight of soil on drill bit per unit area ($WSDB$) is equal to m_c / A_c .

Figure 2
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Figure 2: Clogging assessment of plain mixtures using the universal diagram proposed by Hollmann and Thewes (2013).

Figure 3
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* Hollow symbol means no additive in the soil mixture. The number next to the symbols is the additive content.

Figure 3: Clogging potential assessment of the conditioned mixtures using the diagram proposed by Hollmann and Thewes (2013). Each mixture without additive has the highest clogging potential when different amounts of water were added according to drilling tests in the previous study. For each mixture, the sample with highest clogging potential was used to study the effect of the additive on the clogging indicated as hollow symbols in the figure.

Figure 4
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Figure 4: Properties of mixtures with different content of bentonite at the maximum clogging potential in this study (a) maximum clogging potential of each mixture, (b) consistency index, and (c) shear strength.

Figure 5
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Figure 5: Correlation between the clogging potential and mixture properties for M^0 with CC. (a) Atterberg limits of M^0 with CC, (b) shear strength of the M^0 , and (c) WSDB of M^0 .