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Adhesion of clay to metal surface; Normal and tangential measurement

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Abstract. Adhesion in geotechnical engineering is the interaction between cohesive soil and a solid surface which can cause clogging in mechanized tunnelling through clayey formations. Normal piston pull out and modified direct shear tests were performed on clayey soil samples to determine which type of adhesion stress, normal or tangential, could be most effectively measured. Measured values for normal adhesion ranged from 0.9 to 18 kPa. The range of tangential adhesion was 2.4 to 10 kPa. The results indicate normal adhesion results were more accurate than those for the modified direct shear test that measure tangential adhesion. Direct shear test on identical samples did not show any correlation between measured cohesion and normal adhesion values. Normal adhesion values have shown significantly meaningful variation with consistency index and so are compatible with the base of field clogging assessment criteria. But tangential adhesion and cohesion were not compatible with these assessment criteria.

Keywords: clogging; tunnelling; normal adhesion; tangential adhesion; clayey soils

1. Introduction

Tunnelling through clayey formations experiences such geotechnical problems as long term settlement (Wang *et al*. 2010) or immediate hazards that may be encountered simultaneously with construction as water influx, abrasion and etc. Clogging is a major geohazards risk in mechanized tunnelling through cohesive soils and argillaceous rocks. Clogging results from adherence of clay minerals to metal surfaces and hinders the transport of soil, slows tunnelling and can block forward progress (Thewes and Burger 2004, Atkinson *et al*. 2011). The study of adhesion mechanisms in clayey soils is necessary to prevent or decrease clogging.

Adhesion is the tendency of dissimilar particles or surfaces to cling to one another. Upon materials science, adhesion of two surfaces may result in high adhesion during the normal pull and high friction during sliding, both commonly referred to as Stiction (Bhushan 2003). In the other hand, the problem of adhesion may be encountered when two surfaces are sliding over or pulling

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out from each other. Adhesion force in a soil-steel interface can be subdivided into normal and tangential adhesion depending on the relative movement between the soil and steel. A variety of soil adhesion measurement tests and indirect assessment methods have been investigated to evaluate clogging potential in tunnelling, but no single test method is favored for assessment of the adhesive properties of soil (Sass and Burbaum 2009).

Thewes and Burger (2005) and Geodata (1995) have proposed empirical methods to evaluate clogging potential and use parameters related to soil plasticity as the bases of evaluation. The Geodata method (1995) uses a plasticity index (PI) and natural water content (ω) and the Thewes and Burger method (2005) uses PI and a consistency index (I_c) as the bases of their evaluations. Feinendegen *et al*. (2010) used laboratory and field data to derive a classification scheme to quantify clogging potential based on a consistency index (I_c). Hollmann and Thewes (2013) also used water content, plasticity limits and consistency index as the bases of their new classification for the open shield mod. The value $I_c = 0.75 - 1.25$ signifies the most problematic state of the soil in the Thewes and Burger (2005) method and $I_c = 0.25 - 0.95$ in the Feinendegen *et al*. (2010) method. Fig. 1 shows all four classifications. Researchers hope it may eventually be possible to evaluate clogging potential by determining adherence using a simplified test.

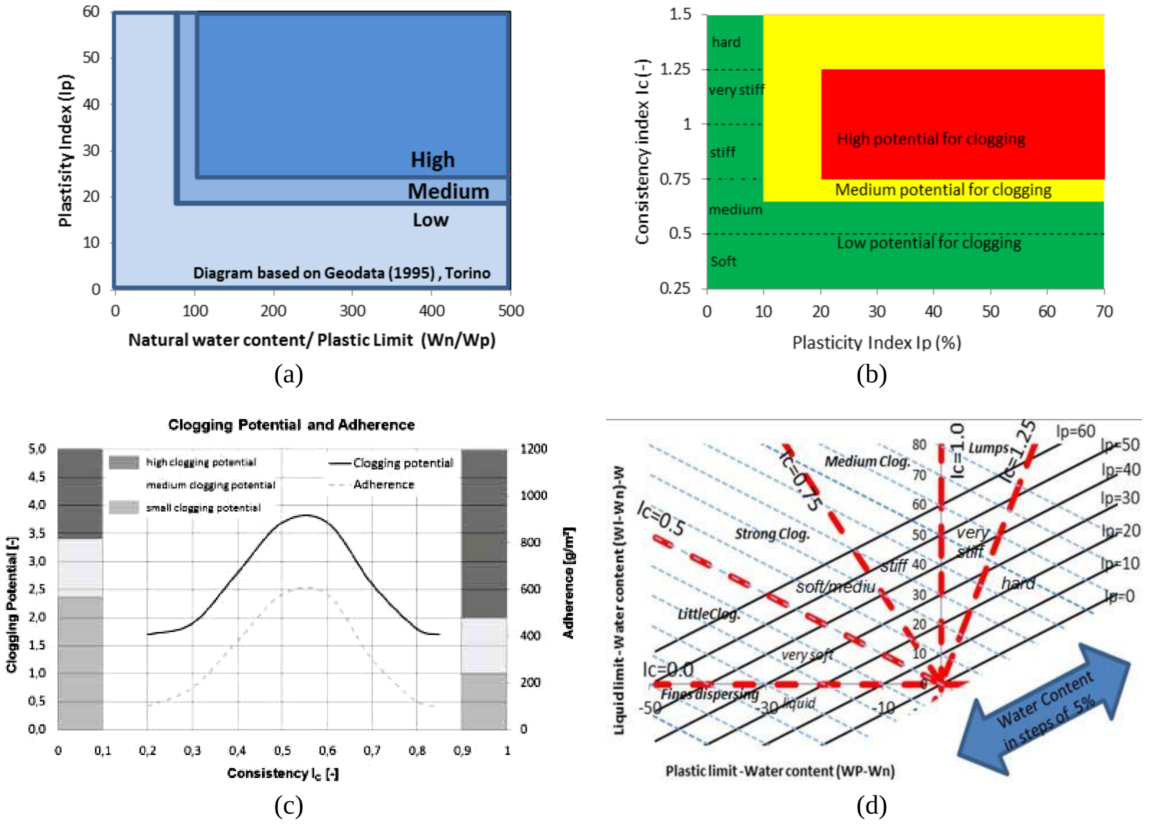


Fig. 1 Empirical clogging assessment methods based on: (a) plasticity and water content (Geodata 1995); (b) Plasticity and consistency index (Thewes and Burger 2005) (refers to fluid supported shield data). (c) Consistency index (Feinendegen *et al*. 2010) (refers to Earth Pressure Balance shield). (d) Water content, plasticity limits and consistency index (Hollmann and Thewes 2014)

The Bangkok metro incident illustrates that the preferred method is the use of an assessment tool to estimate clogging potential in the laboratory and allow calculation of an appropriate additive for excavating soil rather than risk testing of an inappropriate additive on site (Jancsecz *et al*. 1999). There are three categories of laboratory devices to assess adhesion. Those that do not directly measure adhesion include ball and blade tests, mixing tools, rotating plate and Pressurized vane shear test; these provide results from which adhesion force can be calculated (Spagnoli *et al*. 2009, Messerklinger *et al*. 2011, Zumsteg and Puzrin 2012). Another group includes devices that directly measure tangential adhesion, such as the slide, tilt and modified direct shear tests. The third group measures normal adhesion directly. The cone pull-out test and piston separation devices belong in this category (Feinendegen *et al*. 2011, Burbaum 2009, Spagnoli *et al*. 2009, Kooistra *et al*. 1998, SubbaRao *et al*. 2002, Zimnik *et al*. 2000).

The present study used a piston separation device and modified direct shear to assess the best method of detecting adhesion of clayey soil to metal surfaces which allows categorization of soils based on their adhesion potential.

2. Method and material

The piston separation device is a soil mechanic laboratory tool that was applied to measure normal adhesion. The lower sampler of a direct shear test device was modified to measure tangential adhesion between the soil and the metal. An unmodified direct shear test was used to assess cohesion.

The tested clayey soil was made using clay minerals and sand to provide a uniform testing medium in the laboratory. The soil samples were composed of clay powder, dominant montmorillonite and less kaolinite (90% montmorillonite + 10% kaolinite), and different proportions of fine pure sand and they were prepared at different wetness values which demand different ranges of adhesion. The clay powders were supplied by Iran Barite co. and AMIRKABIR technical university laboratory. The powders were first passed through a 0.15 mm sieve to eliminate unwanted particles. The grain size distribution in the clay powders was determined using a hydrometer according to ASTM D422-63 (Fig. 2). The liquid limit (LL) and plastic limit (PL) of both types of sample**s** were assessed according to ASTM-D4318. The specific surface area (SSA) was determined using ethylene glycol in m^2/g. Table 1 summarizes the measured properties of the clay minerals used. Fine sand is an appropriate mixing material to study the clay proportion effect on clayey soil properties (Kim *et al*. 2013). Sand grain sizes were between 0.15 to 0.25 mm. The testing soil samples were prepared by mixing clay samples with compositions of sand with percentages of 0, 10, 20, 30, 40, 50 and 60. To check the plasticity change in the prepared soil samples, the liquid limit and plastic limit were assessed for all samples.

Under laboratory conditions, the oven dried (24h at 60°) soil was weighed and placed in a mixer; sufficient distilled water was added to a specific water content and the specimen was mixed for 15 min. The desired dry density was considered as 1.6 g/cm^3. A spatula was used to place the specimen into the mould in thin layers to minimize trapped air and a straightedge was used to level the specimen.

The Pull out test, soil mechanics laboratory adhesion testing device, comprised a force producer, data logger and data recorder. Fig 3 shows a schematic scheme of the main part of the used device. The soil sampler mould was fixed to the base plate and the motor moved the plate upward into the fixed steel piston (with a roughness of 0.2 μm) to give pressure (7 kPa). After a

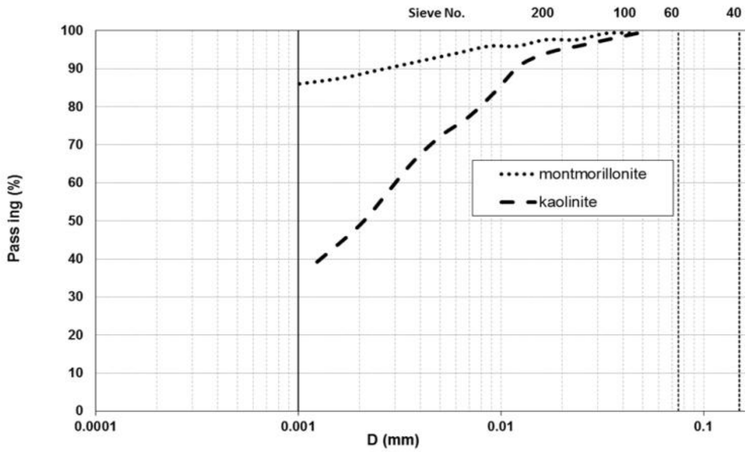


Fig. 2 Particle size distribution of tested clay minerals

Table 1 Physical properties of testing clay minerals

Sample	LL (%)	PL (%)	SSA (m^2/g)*
Montmorillonite	470	75	76
Kaolinite	53	26	8

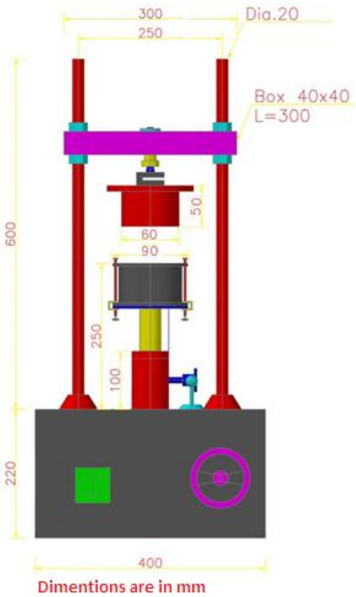


Fig. 3 Schematic scheme of the main part of the adhesion test device

determined time (1 min), the motor reversed and the plate moved downward (separation rate; v = 5 mm/min) and the specimen separated from the piston. The data logger recorded the variation in stress at 0.2 s intervals. The adhesion stress was calculated by dividing the measured tension force

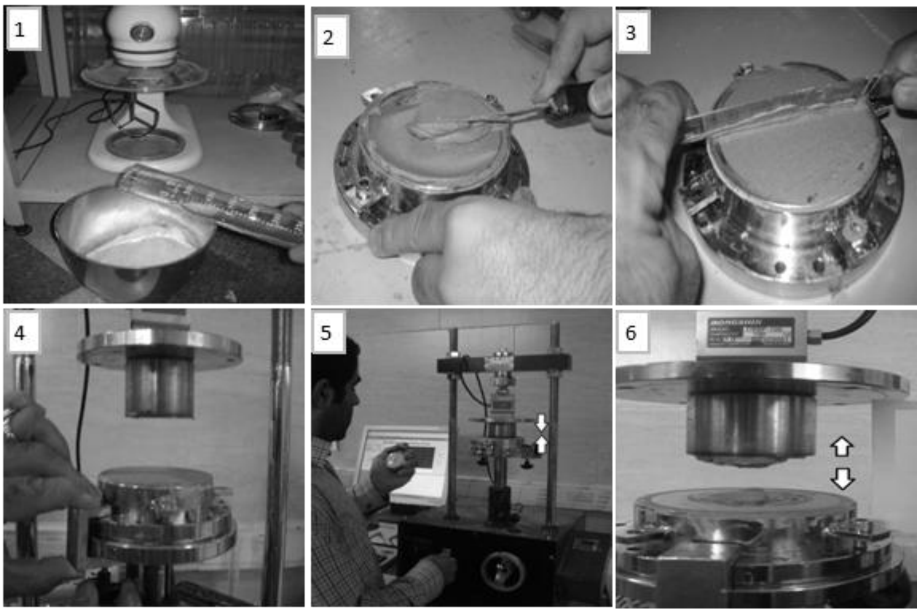


Fig. 4 Sampling and adhesion testing: (1) mixing soil and water; (2) remolding; (3) trimming; (4) placing the mold in the apparatus; (5) compression; (6) separation

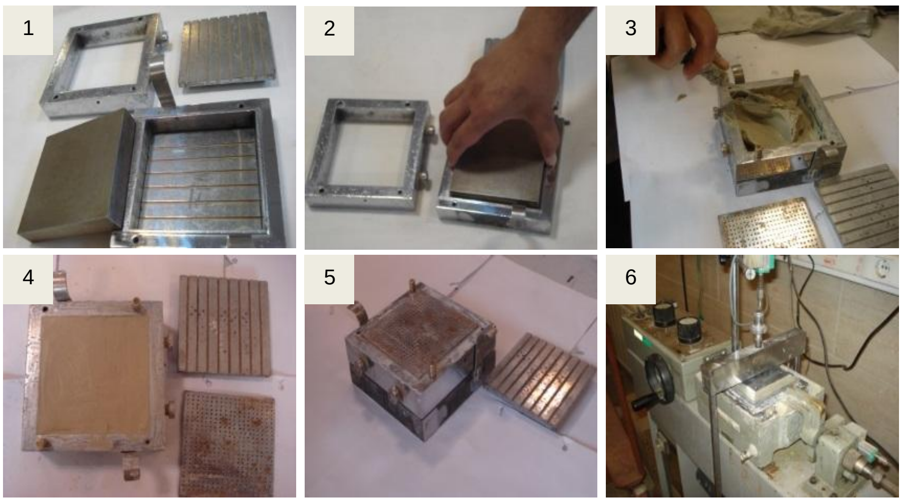


Fig. 5 Modified direct shear mold and testing: (1) mold and metal filler; (2) placing metal filler; (3) remoulding; (4) remolded sample; (5) putting the top plate; (6) test performing

by the area of the piston. The soil sampler mould consisted of five parts that can be assembled and separated to permit up to 4 tests on an unchanged sample, such as the 3 or 4 physical tests recommended (ASTM E691; ASTM E22-82). Fig. 4 shows the steps for soil preparation and adhesion testing (Khabbazi *et al*. 2014).

As past researches have denoted (Thewes and Burger 2005, Sass and Burbaum 2009), side effects affect adhesion test results, then all test conditions such wetting time, speed of piston separation, pretest pressure, contact time and temperature were kept same for all the tests.

The Modified direct shear test used a 10 by 10 cm modified mould. The lower portion of the mould box contained a cubic metal box that allowed shear to occur at the soil-metal interface instead of in the body of the soil as in ordinary direct shear test. Fig. 5 shows the modification of the shear box and the testing steps. As in the ordinary direct shear test, the tests were performed in three steps of increased normal stress.

Cohesion was measured using the direct shear test device with the unmodified 10 by 10 cm sample box. The tests were performed according to ASTM-D3080 and measured undrained cohesion.

The pull out test was performed at 8 different water contents for each soil sample. The modified direct shear test and ordinary direct shear test were performed at 4 water contents (Table 2).

3. Result

The results for normal and tangential adhesive and cohesive sticking stress in clayey soil were recorded and are summarized in Table 2. The sand/clay (S/C) ratio and wetness and their plasticity limits are also recorded in Table 2. As seen, adhesion values differed for similar samples under

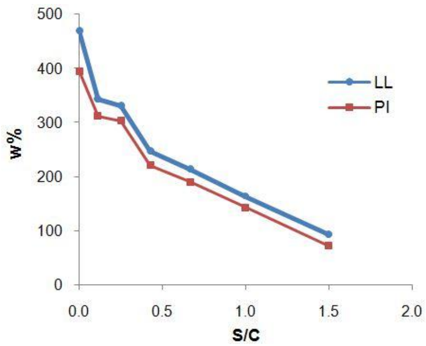
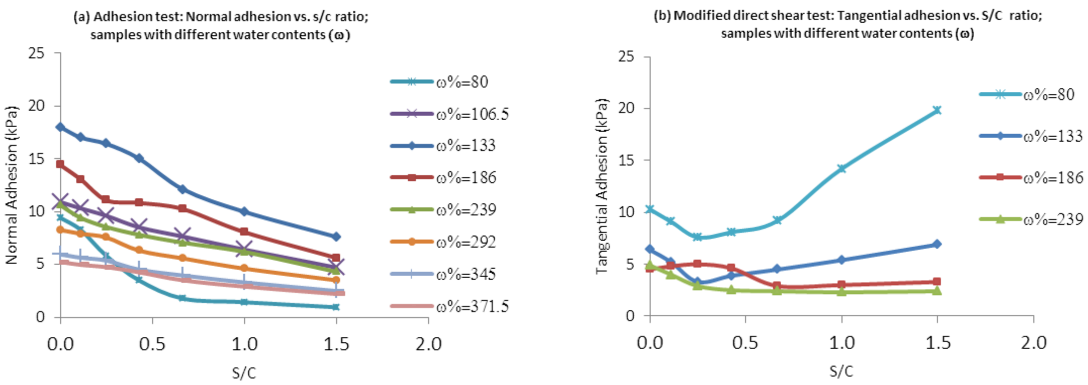


Fig. 6 The variation of liquid limit and plasticity index against Sand/Clay ratio in testing soil samples



(a) Normal adhesion

(b) Tangential adhesion

Fig. 7 Adhesion vs. Sand/Clay ratio in testing soil samples

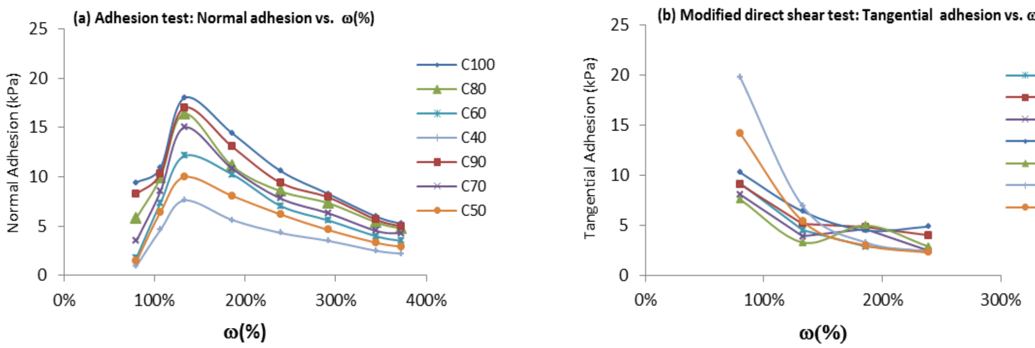
Table 2 Normal and tangential adhesion testing

No.	Sample	Sand (%)	Testing clay (%) (90%m +10%k)*	LL (%)	PI (%)	Normal adhesion (kPa) ω (%)								Tangential adhesion (kPa) ω (%)			
						80	107	133	186	239	292	345	372	80	133	186	239
1	C100**	00	100	470	395	9.4	10.9	18.0	14.4	10.6	8.3	5.9	5.2	17.3	6.4	4.5	4.9
2	C90	10	90	344	312	8.2	10.3	17.0	13.0	9.4	7.9	5.6	4.9	9.1	5.2	4.8	4.0
3	C80	20	80	332	303	5.8	9.6	16.4	11.1	8.5	7.5	5.4	4.7	7.6	3.3	5.0	2.9
4	C70	30	70	247	221	3.5	8.5	15.1	10.8	8.4	6.3	4.5	4.3	8.1	3.9	4.6	2.5
5	C60	40	60	214	190	1.7	7.6	12.1	10.2	7.1	5.6	3.9	3.5	9.2	4.5	2.9	3.7
6	C50	50	50	164	143	1.4	6.4	9.9	8.1	6.2	4.6	3.3	2.9	14.2	5.4	3.0	2.3
7	C40	60	40	93	72	0.9	4.7	7.6	5.6	4.3	3.5	2.5	2.2	19.0	7.9	3.3	2.4

* m: montmorillonite, k: kaolinite
**C100: testing clay = 100%

normal and tangential testing. The values for normal adhesion showed regular variation in response to changes in sample properties. Fig. 6 shows the variation of liquid limit and plastic index of testing soil samples against the S/C ratio. Fig. 7(a) shows a decrease in normal adhesion with an increase in the S/C ratio at all four wetness levels. The range of normal adhesion is 0.9 kPa for sample C80S60 to 18 kPa for C133S00. No significant sensible variation was detected for tangential adhesion against S/C ratio variation. Fig. 7(b) shows that the values for tangential adhesion remained fairly constant as the S/C ratio increased. The variation for tangential adhesion was 2.4 to 17 kPa overall and 2.4 to 6 kPa for three out of four wetness groups.

Normal adhesion was affected by wetness more distinctly. Fig. 8(a) shows an increase in normal adhesion as wetness goes up to a specific value and then a decrease in normal adhesion. These reasonably correspond to the prediction of Burbaum (2009). This variation occurred in all cases and produced similarly shaped curves delineated by S/C ratio. Fig. 8(b) shows tangential adhesion, decreased as wetness increased up to a specific value and became fairly constant thereafter. The curves for these samples overlapped.



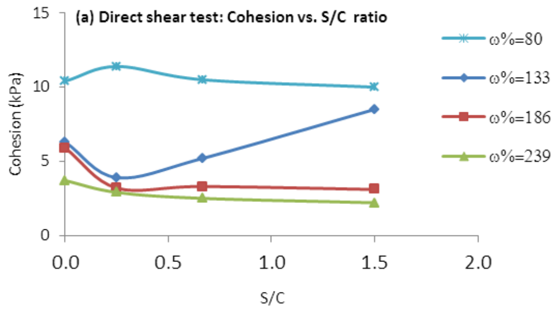
(a) Normal adhesion (b) Tangential adhesion

Fig. 8 The adhesion vs. wetness in clay soil samples with different testing clay contents

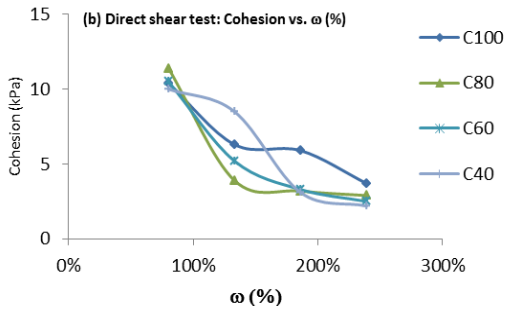
Table 3 Direct shear test results; cohesion values

Testing clay (%) (90%m + 10%k) *	100	80	60	40
Sand (%)	00	20	40	60
ω (%)		C (kPa)		
80	10.4	11.4	10.5	15.5
133	6.3	3.9	5.2	8.5
186	5.9	3.2	3.3	3.1
239	3.7	2.9	2.5	2.2

* m: montmorillonite, k: kaolinite



(a) Cohesion vs. S/C ratio



(b) Cohesion vs. wetness

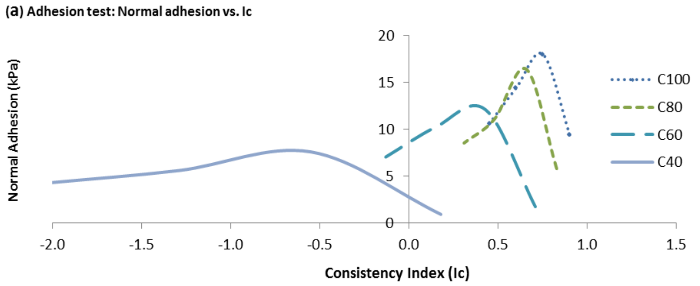
Fig. 9 Direct shear test for clayey samples; with different S/C and water contents

Table 3 shows the cohesion results for the third group of tests that examined direct shear. Cohesion ranged from 2.2 kPa to 15.5 kPa. Fig. 9 shows the variation in cohesion by wetness and S/C ratio. Cohesion showed an irregular trend versus S/C ratio, with the curve for 80% wetness showing the highest level of cohesion (Fig. 9(a)). Moreover, cohesion declined as wetness increased and became constant after a specific value of wetness (Fig. 9(b)).

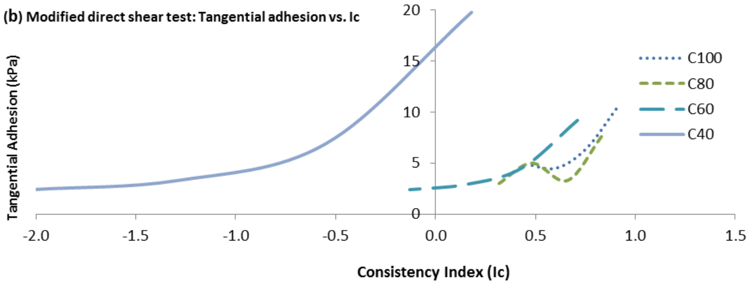
4. Conclusions

Clogging arises from the adhesion of wet clay particles to the metal surfaces of tunnel boring machinery components. Fig. 7(a) illustrates the measured adhesion in normal mode. Any change in a property that affects the adhesion potential of soil is reflected in the normal adhesion test results. For instance, as shown in Fig. 7(a), a regular decrease in adhesion has been occurring as the S/C ratio enhanced. The downturn trend of adhesion value is similar to plasticity reduction when the S/C ratio increases. As Fig. 6 illustrates the liquid limit and plastic index of soil samples regularly drop as the S/C ratio increased. As shown in Fig. 7(a), each level of wetness produced a distinct adhesion curve following the same trend. Soil samples with different adhesion potentials, even a slight difference, could be distinguished by the normal adhesion test.

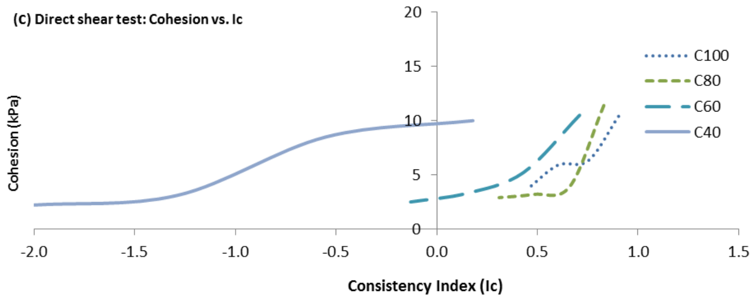
Similarly, Fig. 8(a) shows that the values for the normal adhesion test followed distinct but similar trends according where adhesion varied as wetness varied. This differs from the values for tangential adhesion as measured by the modified direct shear test. Figs. 7(b) and 8(b) show that the trends for soils with different wetness and S/C ratios, respectively, are not distinct. There is no



(a) Normal adhesion



(b) Tangential adhesion



(c) Cohesion

Fig. 10 Adhesion and. Cohesion vs. consistency index (*Ic*)

dominant trend in the curves for adhesion by S/C ratio and a decrease in adhesion with an increase in wetness occurred only in soils with low wetness.

It may be assumed that adhesion potential could be assessed based on cohesion without carrying out any new special test. This assumption arises because the fact that the inherent properties of soils that impress adhesion potential and cohesion are same. Direct shear test results on clay soil samples reject it and show this approach couldn't be adequately accounted for different mechanisms of adhesion. Based on this study, the direct shear test is not an appropriate method for adhesion evaluation as well as clogging potential. Fig. 9(a) shows that testing samples could not be classified according to their undrained cohesion values as measured by the direct shear test. Moreover, no acceptable variation trend could be defined. Fig. 9(b) shows that cohesion decreased gradually as wetness increased, but no distinct levels could be identified for variation in the S/C ratio as evident in normal adhesion test results (Figs. 8(a) and 7(a)).

Two different clogging evaluation criteria, including the Thewes and Burger (2005) criteria (referred for fluid-supported shields) and the scheme which was carried out by Feinendegen *et al*. (2010) (referred for earth pressure balance shield) and the laboratory test results were compared for compatibility. Based on first criteria the more problematic soils showed a clogging potential for fluid supported shield at *Ic* = 0.8-1.2. In addition, the problematic consistency index of second criteria was *Ic* = 0.25-0.90, for which *Ic* = 0.65 indicating the highest adhesion potential.

Fig. 10 shows that the adhesion potential measured by the device had a meaningful relationship with the variation in Ic (Fig. 10(a)), but this was not the case for the other test results (Fig. 10(b) and Fig. 10(c)). Moreover, in the present study the maximum normal adhesion for more adhesive samples observed at *Ic* = 0.45-0.95 (Fig. 10(a)). This is more compatible with the stated criteria by Feinendegen *et al*. (2010) and less by Thewes and Burger (2005). The dynamic of test could be the reason of this case. Since adhesion varies regularly with consistency index and clogging happens as adhesion, then a specific value of Ic could be a unique sign of clogging potential for one group of soils as shown in Fig. 10(a). However, the value may not be identical for all soils. Therefore, the soil with specific fines content as well as adhesion potential has a particular bell curve showing the variation of the adhesion-consistency index. The curve shifts to the left in response to a decrease in fines content also decreases in adhesion. It appears that previous methods could be used as primary criteria, although it is necessary to assess fines content and mineral type adhesion potential in the laboratory.

In conclusion, Adhesion device's ability to assign even a very small adhesion value (0.9 kPa) to a soil sample and distinctly classify the 56 soil samples for a limited range of adhesion recommends use of the piston separation device over the modified direct shear or direct shear tests for adhesion assessment. It is suggested as an appropriate independent adhesion assessment tool.

The adhesion of clayey soil definitely decreased as the S/C ratio increased. The adhesion potential is related to wetness within limits and could be determined for each type of soil using the normal adhesion test. The results of the normal adhesion test are compatible with the base of Thewes and Burger (2005) and Hollmann and Thewes (2013) field and Feinendegen *et al*. (2010) laboratory criteria based on the consistency index. The normal adhesion test results indicate that soil with a specific fine content has a specific bell adhesion-consistency curve and that the shape of the curve depends on the fines content and mineral type.

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