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ORIGINAL PAPER

Assessment of the adhesion potential of kaolinite and montmorillonite using a pull-out test device

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Abstract The tendency of clay particles to stick other surfaces means it is adhesive and can cause clogging of tunnel boring machines. Clogging arising from adhesion hinders or halts tunneling operations. The nature of adhesion in the interaction of soil and metal surfaces must be clarified in order to control its occurrence. This paper investigates the adhesion potential of clayey soil, specifically kaolinite and montmorillonite, by means of laboratory testing. A pull-out test device was used for testing and the test results revealed differences between minerals with respect to adhesion value and behavior. Montmorillonite showed 8 times greater adhesion than kaolinite in both their most adhesive forms. The time until dissipation of adhesion was 15 times greater for montmorillonite than for kaolinite. Montmorillonite adhesion increased and decreased in a bell-shaped curve as the degree of wetness increased. The curve for kaolinite was a gently increasing line. These differences are attributed to differences in the microstructural properties (e.g., CEC, SSA) and dominant sticking mechanism of each clay mineral. The consistency index (I_c) for the most adhesive form of the minerals was 0.25 to 1.99 for montmorillonite and 0.15 to 1.19 for kaolinite. A chart was developed based on the results to illustrate the effect of I_c on the adhesion and clogging potential of the two minerals.

Keywords Adhesion · Clayey soils · Clogging · Kaolinite · Montmorillonite · Microstructural properties

Introduction

Although the sticky behavior of clay minerals is potentially beneficial in some industries, it is a problem in industries such as farming and tunneling (Sass and Burbaum 2009; Burbaum 2009; Burbaum and Sass 2016). Clogging arises when clayey soils stick to tunneling device components and hinders their operation, causing delays. The sticky behavior of clayey soils in contact with surfaces such as those of a tunnel boring machine (TBM) has developed into the studies of adhesion which was started earlier (Schlick 1989; Jancsecz et al. 1999; Atkinson et al. 2003). Solid–solid adhesion, including that between metal and soil, occurs at the points of contact of the two solids. This may result in high adhesion during a normal pull, and high static friction during sliding, both commonly referred to as stiction, a combination of the words stick and friction (Bhushan 2003). Research on adhesion includes analysis of experimental field data and laboratory testing.

Generally, it is not easy to elucidate the adhesion phenomenon between clay-rich soil and material surfaces. The evaluation of adhesion potential in clayey soils involved both indirect evaluation and laboratory measurement. Indirect assessments are based on experimental

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classification based on geotechnical data collected from clogging experienced in previous tunnel projects. Consistency and the Atterberg limits help form these classifications (Geodata 1995; Thewes and Burger 2005; Hollmann and Thewes 2013). Direct measurement is carried out using laboratory testing methods such as the modified direct shear (Kooistra et al. 1998; SubbaRao et al. 2002), ball, sliding, blade, cone pull-out, tilt-plate (Spagnoli et al. 2009), mixing, shear-plate (Zumsteg and Puzrin 2012) and piston separation adhesion or pull-out testing. Piston separation adhesion testing is a direct type of measurement of the tension between the soil and a metal surface. Many researchers examined this method and have offered revisions to the procedure (Thewes and Burger 2004; Satomi et al. 2007; Sass and Burbaum 2009; Fernández-Steeger et al. 2008; Burbaum 2009; Feinendegen et al. 2010; Azadegan and Massah 2012; Khabbazi et al. 2014; Burbaum and Sass 2016). These test results have produced more satisfactory statistical results (Khabbazi et al. 2014). It appears to be possible to develop such a device at a micro-scale to measure micro-scale adhesion between clay minerals and other surfaces, such as was done by Kosoglu et al. (2010) for the friction coefficient of smectite.

The parameters that affect the value of adhesion can be categorized into two groups. The first group comprises the test parameters such as pressure, time, speed of testing, etc. The second group of parameters comprises physical properties of soil such as saturation and permeability (Burbaum and Sass 2016), plasticity (I_p) and consistency (I_c) that interdepend and are controlled by particle size distribution (Fernández-Steeger et al. 2008) and inherent properties of soil that includes clay mineral type, cation exchange capacity (CEC), and specific surface area (SAA). Figure 1 gives a short review of the different parameters and effects on adhesion. The study of these effects helps explain the relationship between the soil properties and adhesion.

The geotechnical properties of clayey soil arise from the microstructure of the clay minerals. For instance, CEC, which it is an index for chemical activity, determines the potential of cohesion in clayey soils (Yukselen and Kaya 2006). Moreover, both cohesive and adhesive forces in clay originate from the electrostatic properties of the clay minerals. The electrostatic properties are directly influenced by the chemical composition of the clay mineral and the crystal structure and, therefore, to CEC (Kooistra et al. 1998). Also, Grim (1962) found that clay minerals with high CEC produce cohesion limits (the wetness at which clay loses cohesion) close to their plastic limit, and which approach their liquid limit in cases of higher CEC. The higher the CEC, the more plastic the clay will behave and also higher levels of cohesiveness and adhesiveness may be expected (Kooistra et al. 1998).

In other words, the force of attraction between clay particles is affected by their geochemical properties such the charge distribution at the surface. Electrical conductivity is representative of the surface charge and is a determining factor for adhesion that affects the repulsive forces between clay particles. Studies that have modified geotechnical parameters under electro-osmosis confirm this point (Zimnik et al. 2000; Fernández-Steeger et al. 2008; Spagnoli et al. 2010a). Atterberg limits, which reveal cohesion potential, can be used as a criterion to show the

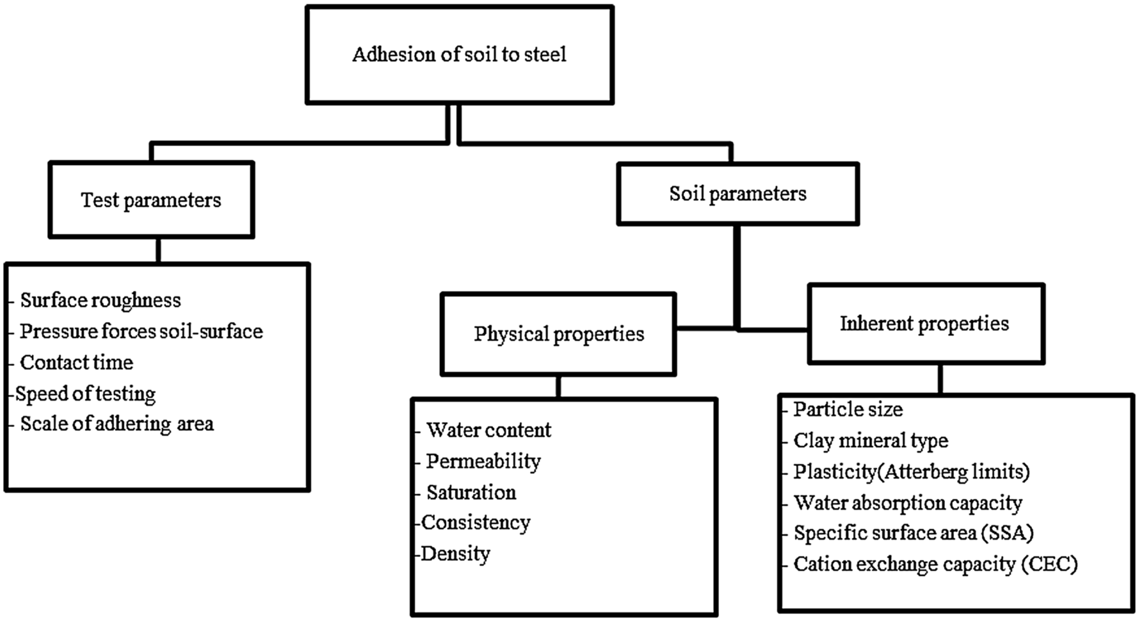


Fig. 1 Effects on adhesion

effect of microstructure on the engineering behavior of clayey soil and they are a major component in adhesion classification of clayey soils (Jancsecz et al. 1999; Spagnoli et al. 2011).

Among environmental parameters, water has an important role in adhesion. The previous studies confirmed that the water film existing in the contact area between the soil and the material surface greatly influences the adhesion characteristic (Fountaine 1954). Tong et al. (1994), Burbaum (2009) and Burbaum and Sass (2016) found that the adhesion force between soil and a solid is mainly comprised of Laplace pressure, meniscus tension and viscous resistance caused by the water film. Also, Jia (2006) showed the role of water in the adhesion force between soil and solid materials caused by attraction forces of the water between the soil and solid materials. Generally, what can be concluded is that the mechanism of adhesion between the soils and foreign materials can be attributed to the water film between the joint surfaces. Wetness is frequently studied as a contributing factor in clogging. Thewes (1999), Burbaum (2009), Weh et al. (2009) and Feinendegen et al. (2011) found that adhesion in very plastic soil is high and decreases as the soil becomes stiffer and more liquid. Clogging mainly occurs in EPB tunnel driving when the excavated material is or becomes plastic. The adhesion when the soil is in a plastic state is high, whereas it decreases for stiff material and when in the liquid side (Spagnoli et al. 2012a). Also, Burbaum (2009) has reported low adhesion for stiff clays and showed that adhesion increases under wetted conditions (Burbaum 2009; Burbaum et al. 2010; Burbaum and Sass 2016). Moreover, when the water-to-clay ratio is low, it can be used as a bonding agent for a variety of materials because the consistency of the mixture is more rigid than plastic and it possesses adhesive properties (Clem and Doehler 1961). Therefore, both inherent physical and environmental factors were considered determinant in clogging investigations.

Kaolinite and montmorillonite clay minerals occur frequently in quaternary deposits and older argillitice formations (Ghafoori et al. 1993). The classification of clay minerals (Table 1) is based on their combination of tetrahedral and octahedral sheets. Kaolinite is a non-swellable clay mineral having the simplest structure and consists of extended tetrahedral and octahedral sheets. Montmorillonite is a swellable clay mineral consisting of octahedral sheets sandwiched between two tetrahedral sheets (Brandenburg and Lagaly 1988). The structures and particle sizes of these clay minerals suggest different levels of adhesion. The present study investigated the adhesion potential of kaolinite and montmorillonite using a piston separation device. The effect of water content was studied for both minerals. The variation in the degree of adhesion and change in consistency was also investigated.

Methods and materials

The present research investigated the influence of clay mineralogy on the adhesion strength of clayey soil to provide a geological countermeasure to the problem of clogging in a TBM. Laboratory testing was carried out on clayey soil samples and the results were compared in graph form. A total of 13 adhesion tests was performed on samples of montmorillonite and kaolinite. The tests were performed at a total of eight water contents for montmorillonite and five for kaolinite. The most relevant geotechnical and clay mineralogical parameters for testing clay minerals were then determined.

The Na-montmorillonite used in this study was provided by Iran Barit Company, Tehran, Iran, and the kaolinite were obtained from the Zonouz region, Tabriz, Iran. The clay was first passed through a 0.15-mm (#100) sieve to eliminate unwanted particles and to determine the clay fraction (CF). The grain size distribution in the sieved soil was then determined using a hydrometer according to ASTM D422-63 (Fig. 2).

The liquid limit (LL) and plastic limit (PL) of both types of sample were assessed according to ASTM-D4318. The specific surface area (SSA) was determined using ethylene glycol in m^2/g (Cerato and Lutenegger 2002) and the CEC was determined in meq/100 g according to ASTM-7503. The properties of the clay mineral powders were determined (Table 2) after heating them in an oven for 24 h at 60 °C.

In the laboratory environment, the oven-dried soil was weighed, placed into a mixer and sufficient distilled water was added to reach the required water content for testing. These were selected based on the plasticity of the clay powders to cover a wide range of consistency. The specimen was mixed for 15 min and left for 24 h (Mixer capacity; 5 kg). A spatula was then used to evenly distribute thin layers of the specimen into a mold to prevent entrapment of air. The mold was over-filled by a few millimeters and the excess soil was then carefully leveled-off using a straight-edge.

A piston separation device was used to assess adhesion. The device consisted of a steel piston (with $d = 6.2$ cm and a roughness of 0.2 μm) that entered the sample surface under the predefined conditions and was then withdrawn (Fig. 3). The prepared mold was fixed to the base plate and a motor moved the plate up toward the piston to provide compression pressure (7 kPa). After a determined time (1 min), the motor reversed movement of the mold downward to allow separation from the piston (separation rate; $v = 5$ mm/min; Fig. 4). A data logger attached to the device recorded variations in the force required for the operation. The software used was specifically designed to record and display the results. The applied force required

Table 1 Classification of clay minerals (Serra 1988)

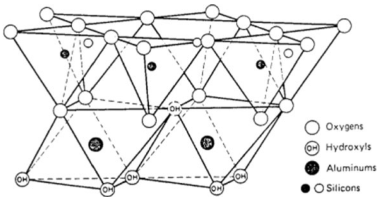
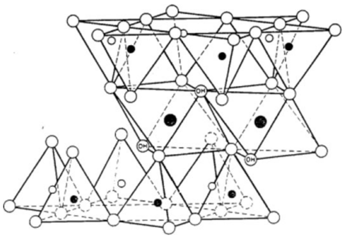
Group	Mineral	Structure	Unit layer	Inter-layer cations	Origin	Structure shape
Kandite	Kaolinite	1 Silica, 1 gibsite	7.1	–	Feldspar, mica (low pH), hydrothermal	
Smectite	Montmorillonite	2 Silica, 1 gibsite	9.7–21	Ca, Na	Volcanic ash, basic rock (high pH)	

Fig. 2 Particle size distribution

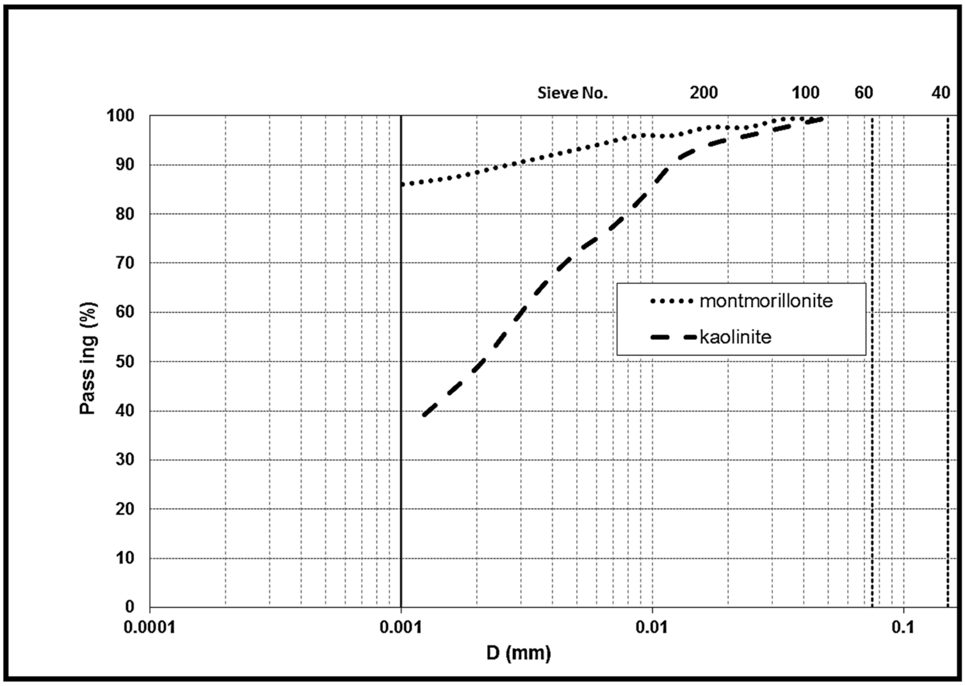


Table 2 Measured characteristics of tested clay minerals

Clay mineral	LL (%)	PI (%)[a]	SSA (m2/g)	CEC (meq/100 g)
Kaolinite	51.5	26	8.3	5.9
Montmorillonite	470	395	800	84

[a] *PI* plasticity index (Ip)

for separation was recorded versus time and the maximum stress were calculated as adhesion and was charted as a time–adhesion stress curve (Fig. 5).

Results

The kaolinite and montmorillonite were tested for maximum adhesion over a range of water contents. The montmorillonite samples were initially tested at six consistency indices (Fig. 5) and each test was repeated 8–11 times to produce a more reliable coefficient of variation (C_v; Table 3).

The small range of plasticity and subsequently limited range of water contents used to test kaolinite produced a limited range of consistency and low variation in

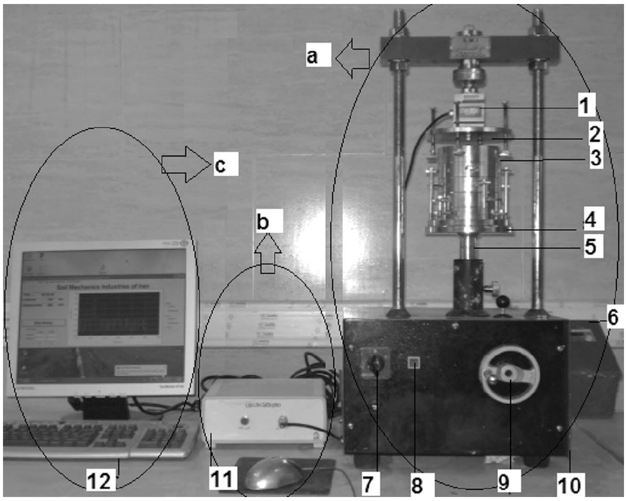


Fig. 3 Piston separation device for piston pull-out test): (*a*) main unit; (*1*) load cell; (*2*) adhering piston; (*3*) mold; (*4*) moving plate; (*5*) force conversion shaft; (*6*) speed control; (*7*) power; (*8*) force direction changer; (*9*) manual force; (*b*) data logger; (*c*) monitor and recorder (Khabbazi et al. 2014)

adhesion (Fig. 6). Moreover, because adhesion was so low, the adhesion measurement couldn't be performed over the attempted range of water contents for kaolinite. Testing was repeated 6–12 times for each sample (Table 3).

The reliability of the results for the variation in adhesion in the montmorillonite samples versus water content was validated by performance of two new tests. The new samples were prepared independently from the previous samples at new water contents (Table 4).

Discussion

The test results were charted to display the highest adhesion values for both minerals (Fig. 7). Each mineral reached their highest adhesion stress value at a unique water content. The difference in the inherent structural properties of the types of the clay minerals, such as SSA, surface charge and CEC, and the effect of these parameters

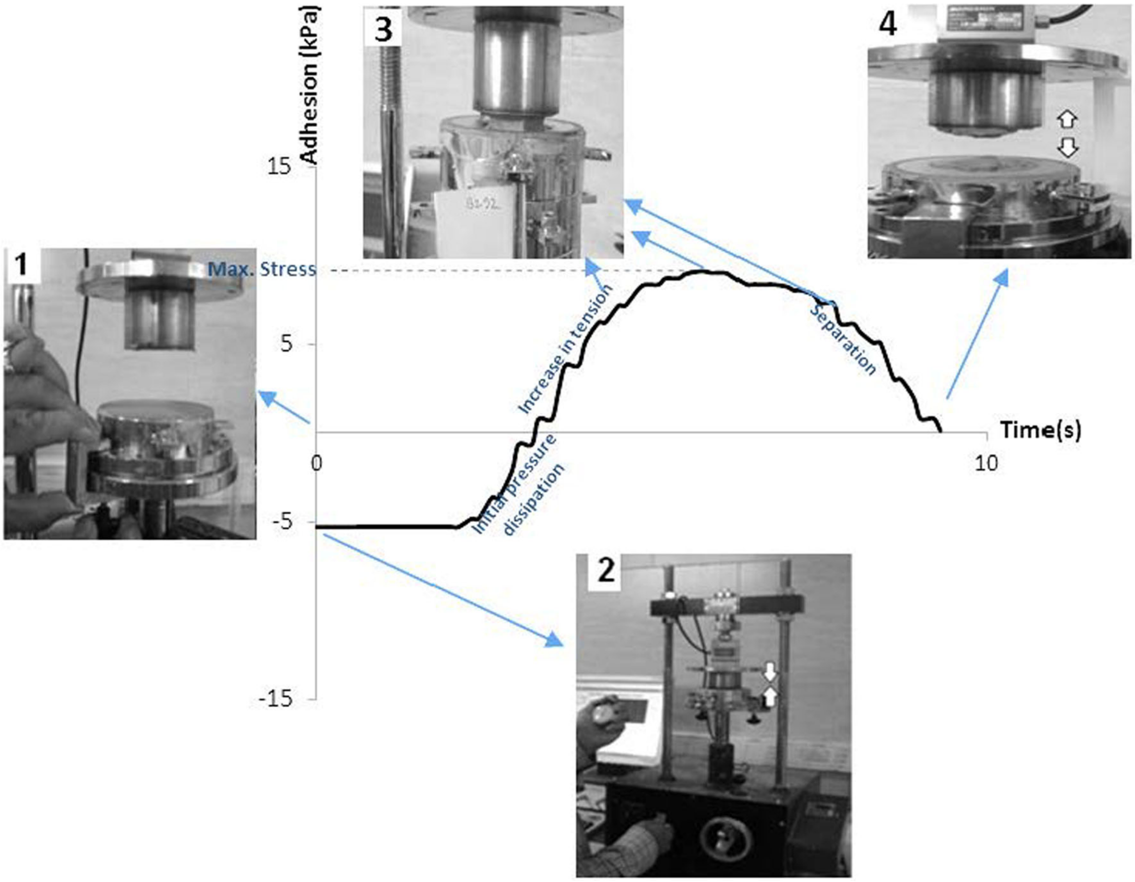


Fig. 4 Adhesion testing and results:(*1*) onset of testing; (*2*) establishment of initial pressure; (*3*) increase in tension with pull-out; (*4*) decrease in tension to zero upon separation

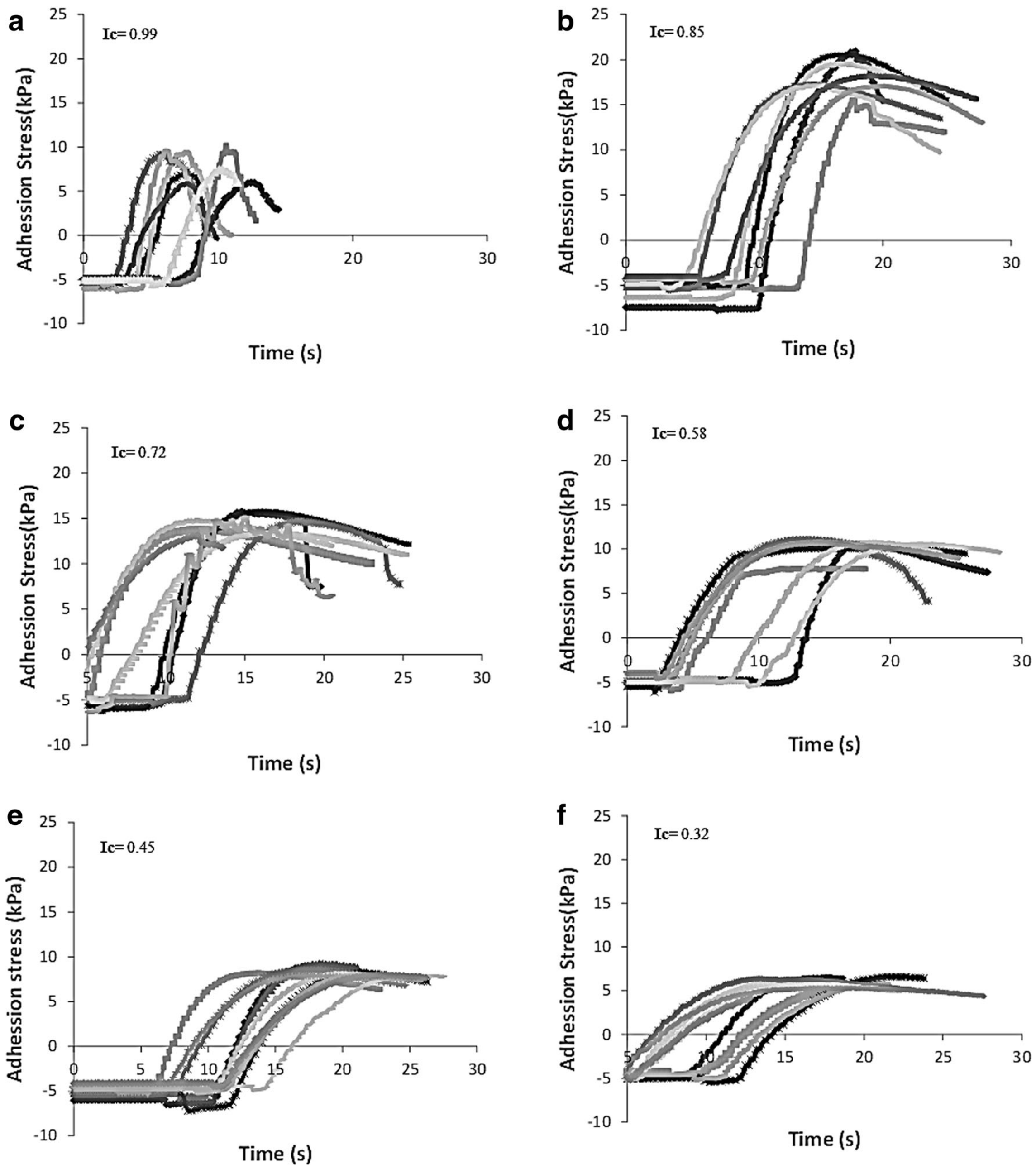


Fig. 5 Adhesion stress versus time for montmorillonite at different values for consistency index (I_c)

on the behavior of clay mineral against water make it reasonable to expect that the adhesion results would also differ according to water content. On this basis, Heuser et al. (2012) also used electro-osmosis on kaolinite and montmorillonite and produced different results for testing minerals. The current test results have revealed the reliability of the variation in adhesion potential between minerals for the specified range of water content.

The first and most obvious difference between the curves (vertical dashed lines in Fig. 7) relate to adhesion value. Montmorillonite displayed an adhesion potential that was eightfold greater than that of kaolinite at most levels of adhesion. The smaller particle size and higher surface charge of montmorillonite was the reason for this difference. As expected from their relative sizes and specific surfaces, montmorillonite has a much greater charge deficiency and many more exchangeable cations than kaolinite; thus, greater adhesion potential. Similar differences in properties of testing clay minerals, such as greater activity, higher plasticity, greater swelling and consolidation, were reported because of the size differences (Warkentin and Yong 1960; Yong and Warkentin 1975; Mitchell 1976). It

Table 3 Adhesion test results for montmorillonite and kaolinite versus wetness

Mineral	No.	ω%	LL (%)	PL (%)	I_c	N	Adhesion stress (kPa)				Laboratory clogging
							Min	Max	Mean	C_v	
Montmorillonite	1	80	470	75	0.99	10	8.8	10.1	9.3	4.5	No
	2	133			0.85	8	17	20	18.0	3.0	Yes
	3	186			0.72	8	13.4	15.5	14.4	2.1	Yes
	4	239			0.58	8	10.3	10.8	10.6	0.8	Yes
	5	292			0.45	11	7.9	8.7	8.2	1.7	Yes
	6	345			0.32	10	5.3	6.6	5.9	6.9	Yes
Kaolinite	1	20	51.5	25.5	1.19	6	0.91	1.93	1.46	7.5	No
	2	29			0.85	9	1.57	2.50	1.75	5.7	No
	3	37			0.54	12	1.60	2.84	1.81	7.7	No
	4	40			0.42	7	1.54	2.35	1.96	6.1	No
	5	47			0.15	8	1.26	2.59	2.04	7.8	No

N number of tests, C_v coefficient of variation, *PL* plastic limit

is, therefore, likely that adhesion of montmorillonite on steel is affected by CEC (linked to its surface charge density). The small size of montmorillonite leads to a greater number of connections and also higher charge effect. Also, for montmorillonite, because of the very high specific surface areas of the particles ($\sim$800 $m^2\ g^{-1}$ in the case of dispersed particles, Leroy et al. 2007), it can be more sticky. However, this is not the case for kaolinite where the SSA is rather low ($\sim$20 $m^2 g^{-1}$ in the case of dispersed particles, Revil 2003).

A smaller particle (in the case of montmorillonite) will cause a capillary tube with a smaller radius, and since the Laplace pressure and meniscus tension are dependent upon the size and shape of the capillary tube produced by in the interface zone (Tong et al. 1994), more air/water menisci in the immediate vicinity of the plate move in such a way as to increase the water tension. Thus, the adhesion is increased.

Since the molecular structure of the water film in montmorillonite–water systems absorbed on the solid surfaces varies due to the inducing effect of the surfaces (Low 1979), and since the bending and fracture of the hydrogen bonds between the induced molecules becomes more difficult (Tong et al. 1994), the viscosity resistance of the water film in the presence of montmorillonite will be increased because of the changing nature of the bulk water; therefore, kaolinite and montmorillonite produced different results for adhesion. Tong et al. (1994) described this event using Eq. 1 proposed by Low (1979):

$$J = J_o \exp(\beta/b) \tag{1}$$

where J represents any given property of the interlayer water, especially viscosity, J_0 are properties of J for bulk water, β is a constant depending upon the nature of the solid surfaces and b is the thickness of the film. For montmorillonite–water systems, b is directly proportional to the ratio of water and soil solid.

Another factor influencing adhesion can be discussed from a physical point of view; smaller soil particles have greater contact with more of the rough surface of a solid, thereby increasing the amount of adhesion. The real contact surface will depend on factors such as the micro-roughness of the metal surface and on clay properties such as shape and size and micro-structural configuration of the clay minerals. The adhesion of the clay will be higher due to the higher real contact area (Kooistra et al. 1998).

It was also found that separation occurred gradually for montmorillonite and was abrupt for kaolinite by comparison. The sharp separation of kaolinite is, however, relative and could be considered gradual when compared with less plastic samples (Fig. 7). The time required for complete separation was 15-fold greater for montmorillonite than for kaolinite (Figs. 5 and 6). The plasticity index (PI) of montmorillonite was similarly greater than that for kaolinite (Table 2). The abrupt separation curves for kaolinite produced a peak, as opposed to the gradual separation curve for montmorillonite for maximum adhesion (horizontal dashed line in Fig. 7). As anticipated from Gouy–Chapman theory, the nature and thickness of the diffuse double layer (DDL) surrounding the clay particles control the attraction mechanism. Similar observations were reported by Sridharan and Venkatappa (1973) and Mitchell (1976) for variation of liquid limit in bentonite. However, the greater number of strong DDL connections in montmorillonite was suggested as the cause of the increased time required for separation. It means more time is needed to separate huge numbers of small montmorillonite particles, as compared to fewer and larger particles of kaolinite, while a constant speed of pull-out was used.

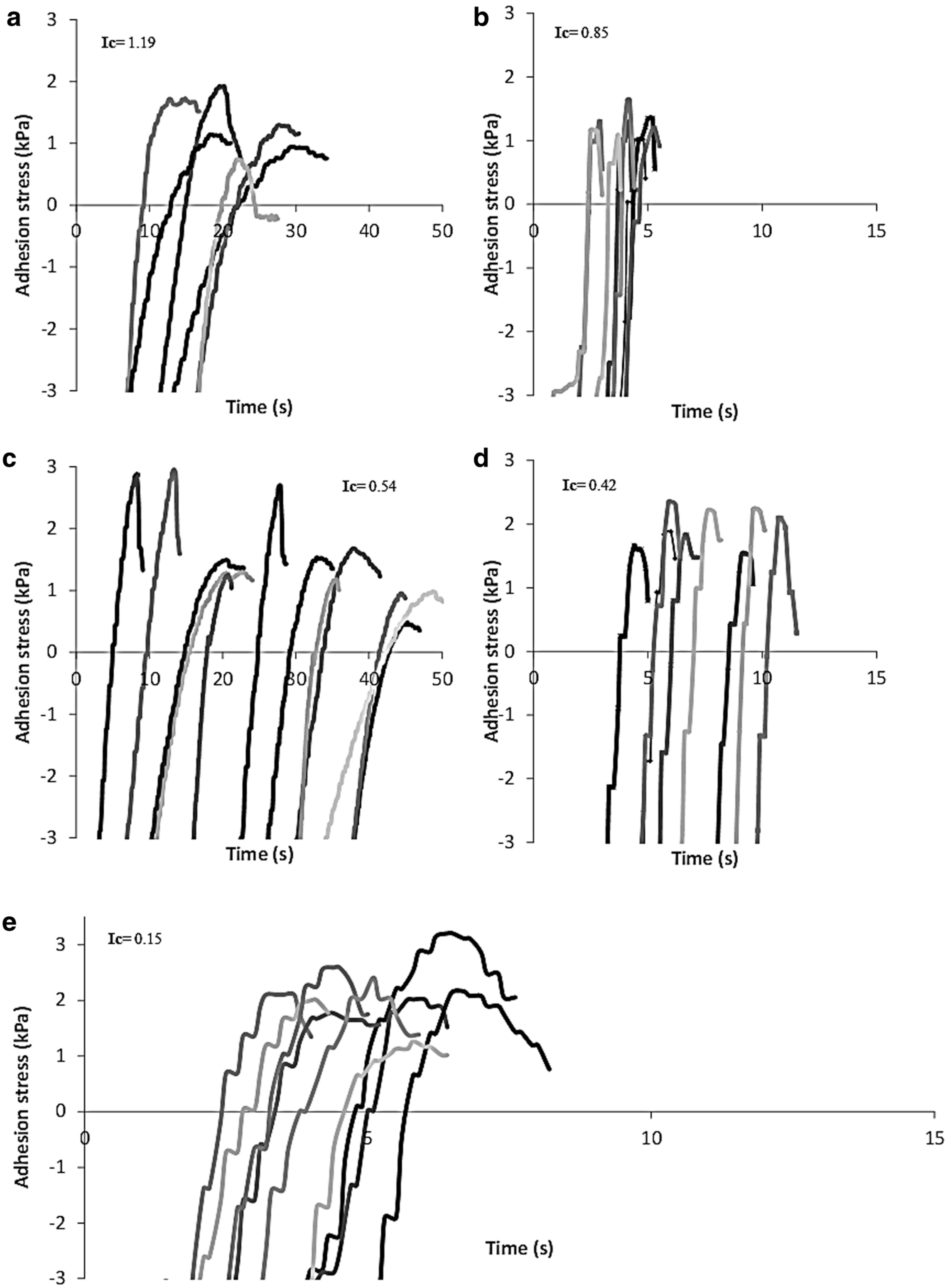


Fig. 6 Adhesion stress versus time for kaolinite at different consistency index values (I_c)

It should be mentioned that the thickness of the DDL is only relevant for swellable clays such as montmorillonite. The DDL does not play an important role for kaolinite, and mechanical properties of kaolinite are controlled by mutual contact among particles (Oslon 1974; Sridharan 2002). The different mechanical behavior may also be explained by the

Table 4 Results of validation tests on montmorillonite samples

Mineral	No.	ω%	I_c	N	Adhesion stress (kPa)		
					Min	Max	Mean
Montmorillonite	1	106	0.92	10	12.7	12.9	12.8
	2	372	0.25	10	5.1	5.4	5.2

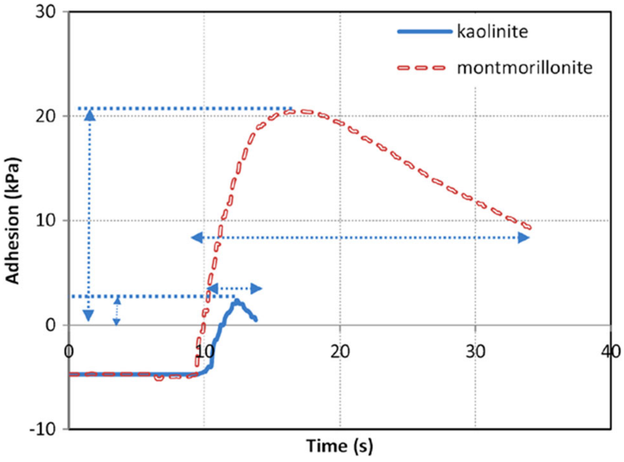


Fig. 7 Adhesion versus separation time for montmorillonite and kaolinite. The *horizontal dashed lines* denote separation time. The *vertical dashed lines* denote adhesion

different CEC of the clays. The CEC of kaolinite is much lower than montmorillonite (60–100 meq/100 g vs. 3–15 meq/100 g for kaolinite, Donahue and Shickluna 1977); therefore, for kaolinite the contribution due to the double layer effect is insignificant and the mechanical parameters are governed at the particle level.

There is also another reason why the separation of the montmorillonite is long. As was mentioned earlier, in montmorillonite, the nature of hydrogen bonds in the water film changes due to the induction by solid surfaces, thereby increasing the viscosity of the water. According to Healey (1926) and Bruyne and Houwink (1951), the time necessary for complete failure to occur, assuming water to be a Newtonian liquid and both solids to be equally wettable, will be $\frac{3\eta V^2}{8\pi F D^2}$ where η = coefficient of viscosity of water, V = volume of water, F = load applied and D = initial distance between plates. Therefore, when water is placed in the vicinity of the soil, its viscosity increases and because of that, the separation takes time.

The clay mineral type plays an important role in the adhesion properties: low-CEC clays have a sticky limit near the plastic limit, and high-CEC clays have a limit further into the plasticity field. Because montmorillonite is the more water-absorbent of the two clay minerals, it has the widest range of plasticity and of moisture-dependent physical properties, such as adhesion. The adhesion values for this mineral (Fig. 8; Table 3) showed meaningful variation. Adhesion increased as wetness increased up to twice the PL, after which an increase in wetness decreased adhesion. When the water content was less than that required for adhesion, no clogging occurred as it did at higher levels of water content. In fact, the maximum point of the bell-shaped curve (Fig. 7) is the same “sticky point” that Fountaine (1954) had mentioned, which may be defined as the minimum soil moisture content at which the cohesion of a soil is less than its adhesion to a foreign object. A soil at this moisture content is just wet enough to cling to a spatula drawn across its surface (Fountaine 1954).

The results demonstrate that adhesion increased as the water content decreased from the LL of montmorillonite. The highest value occurred at $\omega = 138$ % and as wetness decreased more, the tension required for separation decreased. A water content level of 138 % is about twice the PL of montmorillonite. This trend was validated by performance of further testing at two new water content levels that fell within the range of the pretested samples. The results confirmed the trend for adhesion versus wetness (Fig. 9).

Adherence of soil to the piston surface was interpreted here as clogging and signifies that the adhesion force between the soil and metal surface was stronger than the cohesion force between the clay particles. Clogging occurred in the laboratory samples of montmorillonite at the five points of separation; however, the sample at $\omega = 80$ % did not experience clogging. The water content in this sample was less than the water content for maximum adhesion. The force measured in this sample depicts pure adhesion between the montmorillonite and the metal piston surface and was recorded to be 10 kPa. A decrease in wetness after the point of maximum adhesion will decrease the adhesion value.

The adhesion of kaolinite increased as wetness increased up to $\omega = 50$ %, which is near the LL at which adhesion dissipates (Fig. 10). Kaolinite has a limited PI and displays limited variation in its physical properties versus water content. The difference in the curves (Figs. 9, 10) highlights the difference in their adherence behavior. The bell-shaped variation for montmorillonite is not present for kaolinite.

The increasing–decreasing behavior of montmorillonite against wetness also might be explained by accessible water for DDL establishment. Otherwise, when wetness is less than 138 % for tested clay, the water is not sufficient for all particles to establish complete DDL and then contribute in a network of cohesion and also adhesion connections. With further increase of water content, the DDL

Fig. 8 Adhesion versus water content for montmorillonite

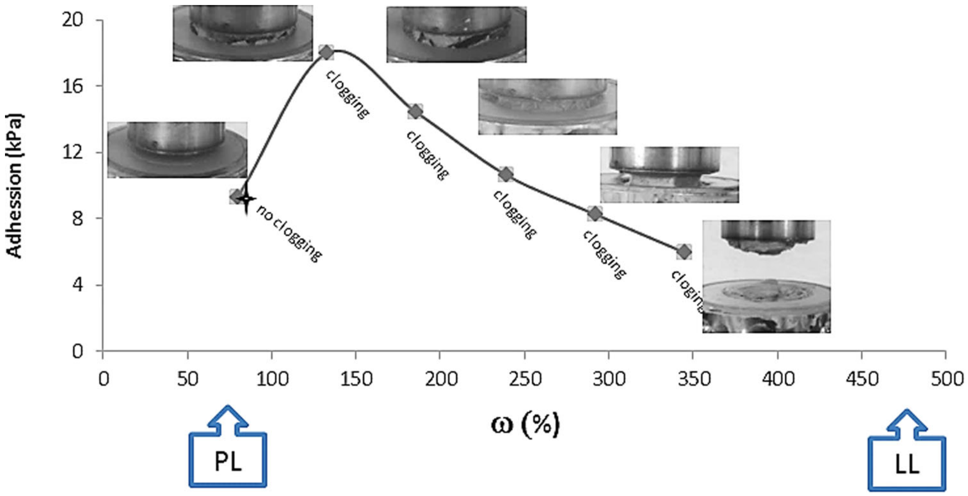


Fig. 9 Adhesion versus wetness in montmorillonite (ω = 106 and 372 %)

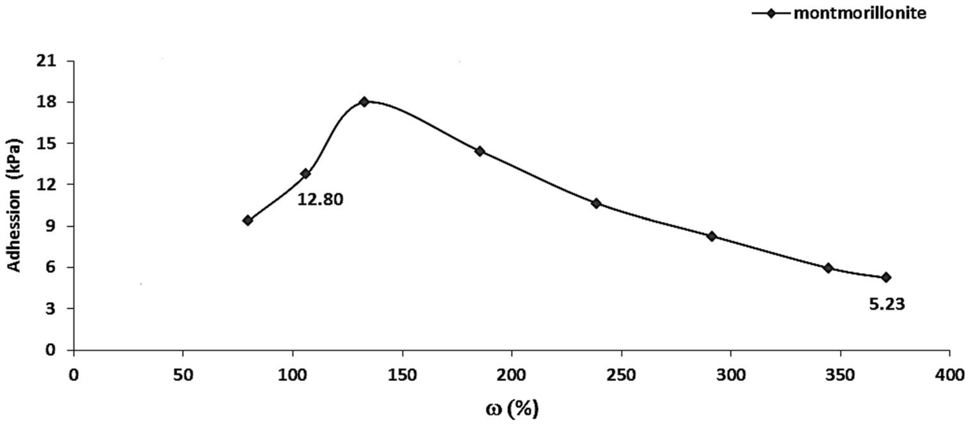
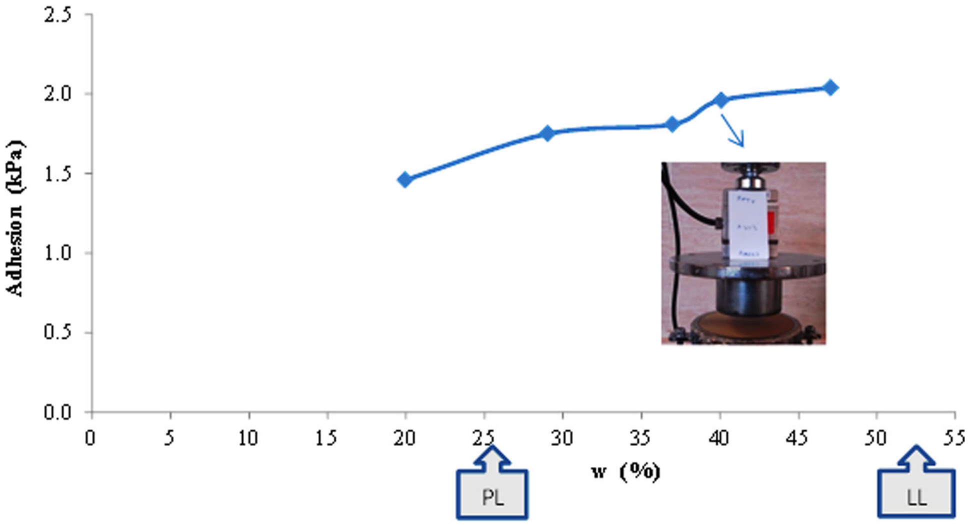


Fig. 10 Adhesion versus wetness for kaolinite



extends, causing the pore water to play a role in decreasing the adhesion force. This continues to the liquid state (LL). The response of clay minerals to the variation in wetness confirms the findings of Oslon (1974), Sridharan (2002) and Spagnoli et al. (2010b) that suggest that the shear behavior shown by kaolinite is controlled by mutual contact. In montmorillonite, it is controlled by the DDL. Heuser et al. (2012) suggested a strong effect of pore fluid

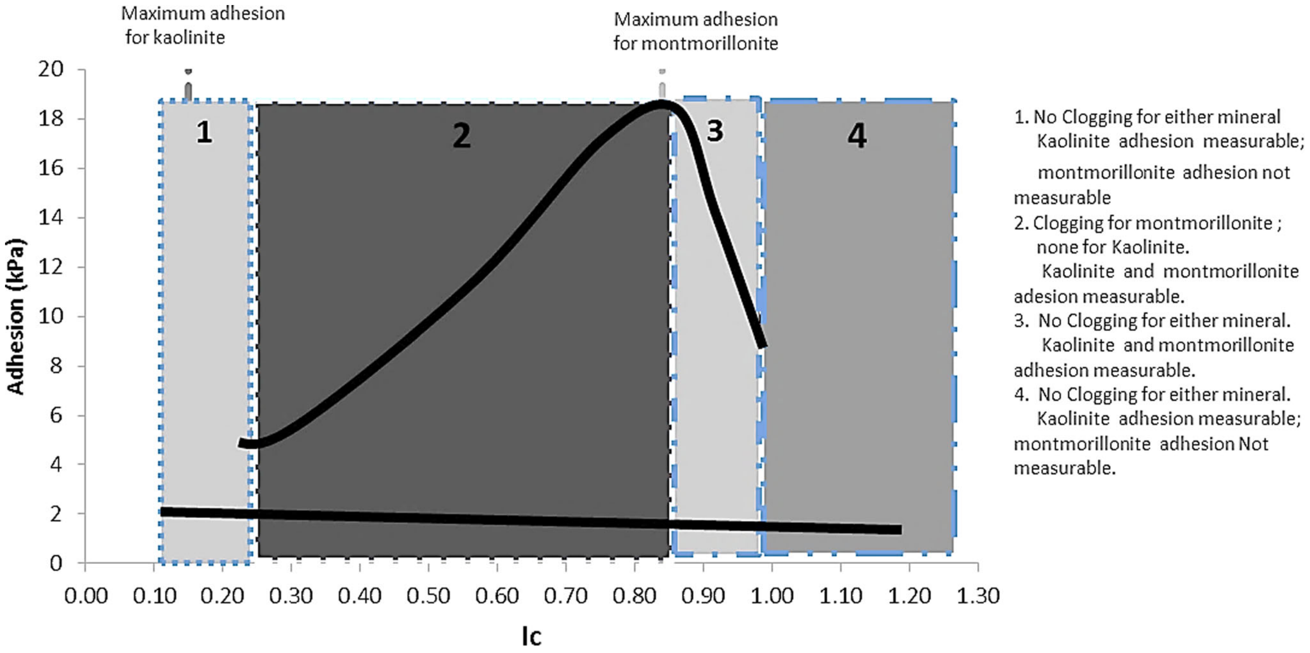


Fig. 11 Adhesion versus consistency index in kaolinite and montmorillonite showing laboratory clogging potential

on smectite and none on kaolinite. At higher consistencies, the behavior of kaolinite and Na-smectite are reversed (Spagnoli et al. 2012b).

The test results for kaolinite and montmorillonite were tested for different values of Ic (Table 3). Earlier studies on plasticity and shear strength of clay minerals have demonstrated that variation in the properties of clay minerals depends on the Ic of clayey soil (Spagnoli et al. 2010b) and the occurrence of clogging is very much dependent on the availability of water and the resulting consistency of the excavated material (Feinendegen et al. 2011). Adhesion was measured at $Ic = 0.15$–1.19 for kaolinite and $Ic = 0.25$–0.99 for montmorillonite. Both minerals show different behavior in response to *I*c (Fig. 11).

Proposed field classification schemes, such as Geodata (1995) and Thewes (1999), have applied the consistency index and Atterberg limits as the basic parameters for assessment of adhesion of clayey soil. The classifications have determined the values of Ic as the dividers for clogging classes. For example, in the classification of Thewes and Burger (2004), the samples with $Ic > 0.75$ show high potential for clogging, and samples with $Ic < 0.75$ show medium potential for clogging. The measured adhesion value in different values of Ic for both tested minerals shows that the mentioned rule cannot always be correct for all clay minerals. The montmorillonite shows a bell-shaped curve for variation of adhesion versus Ic that is similar to that for wetness and the maximum value for adhesion was at $Ic = 0.8$. This is similar to the results of previous studies on soils that have potential for clogging. The curve for kaolinite showed no meaningful trend and a slight decrease.

The differences between kaolinite and montmorillonite for adhesion versus *I*c suggest that the Ic range for adhesion depends on the clay mineral. Not all clay minerals show the same behavior with changes in *I*c and properties such as adhesion for different clay minerals do not behave similarly in response to the same values for *I*c.

Conclusion

The results of a pull-out adhesion test on kaolinite and montmorillonite show differences in adhesion potential in value, adhesive behavior and trend of adhesion value variation in response to wetness variation. The adhesion potential of montmorillonite was eightfold greater than that for kaolinite in their most adhesive forms. This difference in adhesion is considered to be either physical or chemical in nature. In terms of chemical adhesion due to the high specific surface area and high CEC of montmorillonite, which are inherent characteristics of the clay minerals, it was reasonably expected that the adhesion results for montmorillonite would be higher than for kaolinite. For kaolinite, the contribution due to the double layer effect does not play a significant role and the mechanical parameters are controlled at a particle level.

From a physical point of view, the smaller particle size of montmorillonite will cause capillary tubes with smaller radii, and Laplace pressure and the meniscus tension will be increased; thus, adhesion will be increased. In addition, because of that, the smaller particles of montmorillonite more readily enter the microscopic pores of the metal surface, thereby increasing soil-to-metal contact and providing a high level of adhesion.

Montmorillonite showed more plastic behavior against the pulling force, which consumed more time for separation of the test surface from the soil. The results showed a gradual separation for montmorillonite in contrast to the relatively abrupt separation of kaolinite. The separation time for montmorillonite was 15-fold greater than that than for kaolinite in their most adhesive forms. The greater number of strong DDL connections in montmorillonite compared with kaolinite was suggested as the cause of the increased separation time. Another reason is the change in the nature of the hydrogen bonds of water molecules in the water film in the proximity of montmorillonite, which increases the viscosity of water, causing separation of the montmorillonite to take more time.

The trend of variation in adhesion value versus wetness differed between the two minerals. Montmorillonite showed a bell-shaped curve reflecting the increase and then decrease in adhesion as the water content increased. It had a maximum adhesion value of $\omega = 138$ %. The adhesion value of kaolinite increased as the water content increased up to its LL. These different adhesive behaviors reflect their different potential clogging problems. The adhesion of montmorillonite with a metal surface grows stronger than the cohesion between particles as the wetness increases to above wetness of maximum adhesion, which indicates the potential for clogging. The cohesion between particles of kaolinite is generally stronger than its adhesion to a metal surface.

Different ranges for the I_c of adhesion were recorded. Adhesion occurred at $I_c = 0.15$–1.19 for kaolinite and $I_c = 0.25$–0.99 for montmorillonite. It was concluded that adhesion versus I_c is traceable with a bell-shaped peak at $I_c = 0.8$ for montmorillonite and decreasing curve for kaolinite at $I_c = 0.15$. A chart is formed which demonstrates the laboratory clogging potential, adhesion value, trend of variation in adhesion value against I_c variation and measurability of adhesion for kaolinite and montmorillonite.

Certain factors for the occurrence of adhesion are the availability of water as well as swellable clay minerals (clays with high CEC and SSA), while the magnitude of adhesion changes depending on the consistency of the soil.

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