Influence Factors of the Adhesion Strength of Clayey Soil

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Abstract. When earth pressure balance (EPB) shield tunnels are constructed through clayey ground, the soil adheres to the cutter and cutterhead due to the high adhesion strength between the steel and the clay. To investigate the influence of different factors on the adhesion strength, this study used montmorillonite, kaolin and mixtures of the two as test soils. The adhesion strength between steel and clay was determined with a customized rotary shear apparatus. The results show that the adhesion strength between the steel and the clay increased with the consistency index. As the consistency index decreased, the effect of the normal pressure on the adhesion strength gradually weakened. As the contact angle of the shear plate increased, the adhesion strength decreased. The plasticity index had little effect on the adhesion strengths. The adhesion strength increased gradually with increasing surface roughness. The most important factors which influenced the adhesion strength are the soil consistency index, the normal pressure and the contact angle of the shear plate.

Keywords: EPB shield · Clayed soil · Adhesion strength

1 Introduction

The earth pressure balance (EPB) shield has been widely used in urban metro construction due to its high efficiency and safety (Herrenknecht et al. 2011; Zumsteg et al. 2012; Ye et al. 2016; Liu et al. 2018). When the EPB shield crosses a soil layer with a high clay mineral content, the muck may adhere to the cutterhead and cutters. The EPB shield becomes clogged and is not able to tunnel.

The main reason for shield clogging is the high adhesion strength between steel and clay. However, the adhesion between steel and clay is a complex problem and is influenced by several factors, such as the clay state, clay water content, normal pressure, and steel surface state. Some researchers have conducted related studies. Sass and Burbaum (2009) studied the effects of material type, steel surface roughness and normal pressure on the adhesion strength of clay on different materials using a customized apparatus. Spagnoli (2011) and Feinendegen et al. (2010) determined the variation in the adhesion of clay with the consistency index I_c by cone pull-out testing. Liu et al. (2018) reported that the adhesion strength first increased and then decreased with an increase in the consistency index of clay, and the adhesion strength reached a maximum value when

Y. Liu et al. (Eds.): GeoChina 2021, SUCI, pp. 57–64, 2021.
https://doi.org/10.1007/978-3-030-80316-2_6

the consistency index was approximately 1. Azadegan and Massah (2012) reported that when the temperature increased from 5 °C to 30 °C, the adhesion strength decreased by 82%. The surface tension of the moisture in the soil decreased continuously with an increase in temperature, resulting in a decrease in adhesion strength. Zumsteg and Puzrin (2012) used a customized shear plate apparatus to investigate the effect of roughness, water content and normal pressure on the adhesion strength between steel and clay and concluded that the adhesion strength increased with the roughness of the steel surface and the normal pressure and that the relationship between the adhesion strength and the water content was logarithmic.

Thus, the adhesion strength between steel and clay can be affected by the clay type, the soil consistency index, the metal hydrophilicity, the surface roughness and the normal pressure. However, the existing research does not fully explore the impact of various factors on adhesion strength. The paper investigated the variation in adhesion strength between steel and clay was investigated considering the consistency index, normal pressure, plasticity index, contact angle and plate surface roughness using a rotary shear apparatus.

2 Testing Materials and Approaches

2.1 Testing Materials

The testing soils contained montmorillonite, kaolin and mixtures of the two. Montmorillonite and kaolin were mixed at mass ratios of 3:1 (M_1), 1:1 (M_2) and 1:3 (M_3). The Atterberg limits of the tested soils are shown in Table 1.

Table 1. The Atterberg limits of the clays

Tested soil	Plastic limit (%)	Liquid limit (%)	Plasticity index
Montmorillonite	59.9	316.8	256.9
Mixture 1 (M_1)	52.5	254.0	201.5
Mixture 2 (M_2)	34.3	156.7	122.4
Mixture 3 (M_3)	32.4	98.0	65.6
Kaolin	31.8	56.2	24.4

The tested metal plate was made of 303 stainless steel with a surface roughness of 0.34 μm. When the influence of the surface roughness was investigated, the adhesion strength was determined using shear plates made of 303 stainless steel with surface roughnesses of 0.34, 4.84 and 11.03 μm.

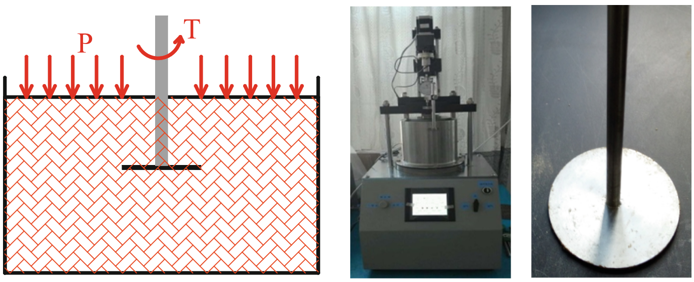
The contact angle θ refers to the angle between the tangent line of the gas-liquid interface and the solid-liquid boundary line at the intersection of a gas, liquid and solid. When the liquid is water, the contact angle characterizes the hydrophilicity of the solid material. The contact angle is related to the material properties. When the influence of the contact angle was investigated, the adhesion strength was determined with shear plates made of Cr12MoV mold steel, 45 steel, Q235 steel, 303 stainless steel, polyoxymethylene (plastic) and polyethylene (plastic). The contact angles of the steels are shown in Table 2.

Table 2. Parameters of the shear plates

Material	Contact angle (°)
Cr12MoV mold steel	58.96
45 steel	58.76
Q235 steel	57.15
304 stainless steel	62.04
Polyoxymethylene (POM)	78.32
Polyethylene (PE)	94.51

2.2 Rotary Shear Test

The adhesion strength between the steel and clay under different normal pressures was measured using a customized rotary shear apparatus, as shown in Fig. 1 (Liu et al. 2018). The rotary shear apparatus contains a motor, specimen box, loading device and shear plate. Soils with a consistency index of less than 0.4 are too soft to ensure the pressure tightness of the screw conveyor, whereas soils with a consistency index > 0.75 are too stiff to be used as a supporting medium (Thewes and Budach 2010; Hollmann and Thewes 2013). Thus, the range of the consistency index values of the soil specimens was appropriately expanded and was determined to be 0.1 to 1.0, at which the adhesion strength reached the maximum value (Liu et al. 2018). The testing conditions are listed in Table 3.



(a) (b) (c)

Fig. 1. Rotary shear apparatus: (a) schematic diagram, (b) photo of the apparatus and (c) shear plate

Table 3. Overview of the testing conditions

Parameter	Values
Consistency index	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0
Normal pressure (kPa)	100, 200, 300, 400
Plasticity index (I_p)	24.4, 122.4, 256.9
Contact angle (°)	57.15, 58.67, 58.96, 62.04, 78.32, 94.51
Surface roughness (μm)	0.34, 4.84, 11.03

The test procedures were as follows. The box of the rotary shear apparatus was filled with soil in layers. Then, the top plate was positioned on the soil specimen. A certain normal pressure was applied to expel the air between the top plate and the soil specimen. Then the exhaust valves of the test equipment were closed and the desired pressure was applied to the specimen. After the normal displacement of the top plate of the box became stable, the shear plate was rotated at a velocity of 20°/min. The torque was recorded, and the adhesion strength was calculated with formula (1). The detailed test procedures of the rotary shear test can be found in Liu et al. (2019).

$$a = \frac{6T}{\pi D^3} \tag{1}$$

where a - the adhesion stress between the clay and steel, T - the torque measured by the torque sensor, and D - the diameter of the steel plate.

3 Test Results

3.1 Variation in the Adhesion Strength with Respect to the Consistency Index

The adhesion strength between the M_2 mixture and the 303 stainless steel was determined at different consistency index values (Fig. 2). The normal pressure was set to 50, 100, 200 and 300 kPa. The adhesion strength initially increased slowly and then increased rapidly with increasing consistency index. The adhesion strengths under different normal pressures were similar as the consistency index was less than 0.6. While the consistency index was higher than 0.6, the difference in the adhesion strengths under different normal pressures increased markedly.

3.2 Variation in the Adhesion Strength with Respect to the Normal Pressure

The adhesion strength between the M_2 mixture and the steel was determined at normal pressures of 50, 100, 200 and 300 kPa to study the effect of normal pressure on the adhesion strength. The consistency index (I_c) values of the soil specimens were set to 0.4 and 0.8, as shown in Fig. 3. When the consistency index was 0.8, the increase in the adhesion strength decreased with an increase in the normal pressure. When the consistency index was 0.4, the adhesion strength remained almost constant with increasing

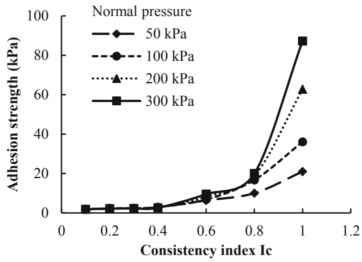


Fig. 2. Variation in the adhesion strength with the consistency index under the normal pressures of 50, 100, 200 and 300 kPa

normal pressure. Since the soil specimen with a consistency index of 0.4 was almost saturated, the normal pressure was supported by the pore water in the soil sample. Thus the normal pressure has little effect on the adhesion strength. As the consistency index increased, the soil saturation decreased. The normal pressure would have a significant influence on the adhesion strength.

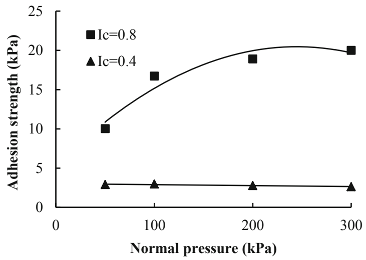


Fig. 3. Variation in the adhesion strength with respect to normal pressure

3.3 Variation in the Adhesion Strength with Respect to the Plasticity Index

The adhesion strengths between the steel and the montmorillonite, kaolin, and the M_2 mixture were determined at the normal pressure of 100 kPa to study the effect of the plasticity index I_p on the adhesion strength (Fig. 4). No major difference was observed in the adhesion strengths among the clays at the same consistency index value. This result indicated that the plasticity index had a limited effect on the adhesion strength if the soil consistency states were similar.

3.4 Variation in the Adhesion Strength with Respect to the Contact Angle

To study the effect of contact angle on adhesion strength, shear plates made of the Cr12MoV mold steel, 45 steel, Q235 steel, 303 stainless steel, polyoxymethylene and polyethylene were tested. The adhesion strength between the different shear plates and the clay was measured at a normal pressure of 100 kPa (Fig. 5). The adhesion strengths of clay decreased with an increase of contact angles. Since the contact angles of the

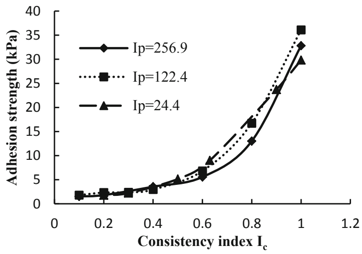


Fig. 4. Variation in the adhesion strength with respect to the consistency index for different clays under a normal pressure of 100 kPa

tested metal materials ranged from 57.15° to 62.04°, there were no large differences in the adhesion strength among the different metal materials. However, the adhesion strengths between the two organic plastics and the clay were significantly lower than those between the metals and the clay due to the much higher contact angles of the plastics. Therefore, the effect of contact angle on adhesion strength is great; however, the metal materials do not have different adhesion strengths due to their similar contact angles.

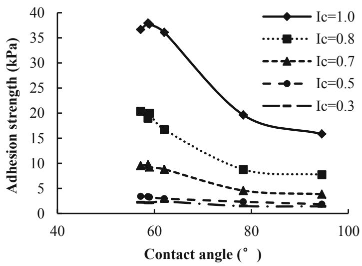


Fig. 5. Variation in the adhesion strength with respect to contact angle under a normal pressure of 100 kPa

3.5 Variation in the Adhesion Strength with Respect to the Surface Roughness

To study the effect of surface roughness on the adhesion strength, the adhesion strengths between the M_2 clay mixture and the steel plates with surface roughnesses of 0.34, 4.84 and 11.03 μm were determined at normal pressures of 50 and 100 kPa (Fig. 6). The adhesion strengths of the shear plates with different surface roughnesses remained basically constant as the consistency index was low. At higher consistency index values, the adhesion strength increased with the surface roughness. However, the effect of surface roughness on the adhesion strength was generally not significant.

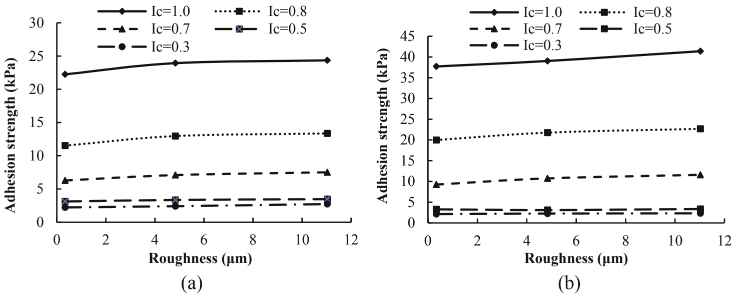


Fig. 6. Variation in adhesion strength with respect to surface roughness at different consistency index values under normal pressures of (a) 50 kPa and (b) 100 kPa

4 Conclusions and Prospects

When the consistency index of the soil specimen was less than 1, the adhesion strength between the steel and the clay increased with an increase in the consistency index. As the consistency index decreased (i.e., as the water content and saturation of the soil specimens increased), the effect of the normal pressure on the adhesion strength gradually weakened. As the contact angle of the shear plate increased, the hydrophilicity gradually decreased, and the adhesion strength decreased. When the soil specimens with different plasticity index values had the same consistency index, the resulting adhesion strengths were similar. The adhesion strength increased gradually with an increase in surface roughness. The most important factors which influenced the adhesion strength are the soil consistency index, the normal pressure and the contact angle of the shear plate.

As stated in the paper, the hydrophilicity of the cutterhead and cutters in the EPB has significant effect on the adhesion strength. Thus, how to make hydrophobic cutting tools is a key technology to avoid EPB clogging.

Acknowledgments. The financial support from the National Natural Science Foundation of China (No. 51778637) and the National Key R&D Program of China (No. 2017YFB1201204) are acknowledged and appreciated.

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