ELECTROCHEMICAL REDUCTION OF LOESS ADHESION ON SHIELD MACHINE CUTTING TOOLS

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ABSTRACT: Loess from northwest China demonstrates transitional behavior between clays and poorly graded sands, and, following weathering, releases both cations and anions. The prevalence of alkaline environments in this region further alters the electrochemical properties of loess. This study investigated the electrochemical reduction of loess adhesion on shield cutting tools through plate sliding, plate pull-out, and electroosmosis flow experiments. Results showed that cations with high electrovalence reduced the Debye length and decreased the absolute value of electrokinetic potential (below 25 mV). While anions generally reduced both normal and tangential adhesions, the presence of SO_4^{2-} and Na^+ after ionization unexpectedly increased adhesion by diminishing electrostatic repulsion. Acidic pH conditions also reduced the Debye length and absolute value of electrokinetic potential. Lower contact angles, compared to pure loess, indicated higher fluid viscosity and reduced capillary tension, conferring testimony supporting these arguments. Electroosmosis was found to be effective in reducing adhesion, except when $MgCl_2$ and $AlCl_3$ additives were present. In these cases, the high electrovalence of the cations induced 'reversed' electroosmosis flow. The insights gained from this study advance the understanding of electrochemical reduction of loess adhesion on shield machine cutting tools.

1. INTRODUCTION

Adhesion significantly increases safety risks and leads to clogging during tunnel excavation, particularly in clayey soils or mixed ground containing clay layers of high plasticity (Zumsteg et al. 2016). The critical particle size for clogging has been identified as 0.15 mm. Clogging can occur at various stages of excavation, resulting in reduced advance rates and considerable challenges in spoil discharge. To address this issue, engineers have employed soil conditioners to modify the rheological properties of soils and mitigate clogging. Key factors influencing clogging potential include water content, metal surface roughness, and the proportion of additives used. Comparative analyses of clayey soils, such as bentonite and kaolin, have shown that mixtures containing bentonite exhibit a higher clogging potential than pure kaolin (Kang et al. 2019). However, the fundamental relationship between electrochemical properties (e.g., electrovalence and environmental pH) and adhesion remains poorly understood.

In general, a thinner fluid film at the soil–metal interface results in increased adhesion. Both fluid viscosity and capillary tension contribute to this phenomenon; however, the effect of capillary tension can often be neglected, as its development requires more vigorous conditions, such as minimal contact at the soil–metal interface. Numerous experiments have investigated the use of polymers for macro-morphological modification of tool surfaces (Soni & Salokhe 2006). These studies found that soil at the sticky limit exhibited the highest normal adhesion (3–7 kPa), while the introduction of surface protuberances reduced tangential adhesion by 10%–30% and normal adhesion by 10%–60%. variety of methods and devices have been developed to assess the adhesion of clayey soils to shield cutting tools. For example, an empirical stickiness ratio—determined by weighing the soil adhering to a mixing tool after soil preparation—has been introduced to assess clogging potential (Zumsteg & Puzrin 2012). Additionally, a pull-out test device has been utilized to evaluate the adhesion of kaolinite and montmorillonite (Khabbazi et al. 2019). Results showed that montmorillonite adhesion followed a bell-shaped curve with increasing water content, whereas kaolinite adhesion increased continuously.

In addition to the development of methods and devices for assessing soil adhesion, there is a strong demand for adhesion reduction strategies within agricultural industries, as there are essential for enhancing the productivity of terrain machinery (Massah et al. 2021). Previous investigations have examined the effect of dispersants on tangential adhesion at the clay-metal interface, revealing that soils with a consistency index below 0.4 are optimal for spoil discharging. The feasibility of employing electro-osmotic techniques to mitigate soil adhesion has also been evaluated (Li et al. 2025), with experiments considering variables such as water content, holding time, applied voltage, and duration of application, thereby validating the potential of electro-osmotic approaches for adhesion reduction. Despite the relative merits of these studies, notable research gaps remain, particularly regarding the relationship between electrochemical properties and loess adhesion, as well as the underlying mechanisms governing loess adhesion reduction. The main objectives of this study are to: (i) establish the connection between electrochemical properties and loess adhesion; and (ii) elucidate the inherent mechanisms responsible for adhesion reduction.

2. MATERIALS AND METHODS

2.1 MATERIALS

The soil applied in this study was sampled from Loess Plateau in northwest China, at a depth of 4-5 meters below ground surface. Soil grading was performed in accordance with ASTM-D4318-17, indicating a composition of 5% sand, 85% silt, and 10% clay.

2.2 METHODS

In this study, a modified apparatus was employed to measure both tangential and normal adhesion at the soil–metal interface, comprising an inclined plate sliding module and a flat plate pull-out module. The inclined plate could be stably tilted at angles ranging from 0° to 90°, controlled by a wheel. The plate, measuring 400 mm in length and 300 mm in width, was hinged to a steel frame at one end and connected to a hand-cranked steel strand at the other. Soil samples were prepared by weighing and mixing the dried soil according to the specified additive ratios. The desired configuration was achieved at a fixed consistency index, utilizing the well-known relationship among soil consistency index, plasticity index, and moisture content. The flat plate pull-out test was conducted by attaching elastic slings to the test specimen. The dynamometer was used to gradually lift the soil sample until it detached from the metal plate. A tensile gauge, with a minimum graduation of 0.01 N, continuously measured the increase in tension over time, and the maximum value (F_{max}) was recorded. Tangential adhesion is influenced by both normal force and interfacial friction.

The electroosmosis tests, which were based on the inclined plate sliding test and the flat plate pull-out test, involved applying an external electric field to soil samples mixed with cations or anions using a DC power supply. The metal plate in contact with the bottom surface of the soil sample served as the cathode, while the metal plate in contact with the top surface acted as the anode. A voltage of 5V was employed throughout the electroosmosis tests. Upon completion of the electroosmosis treatment, both the flat plate pull-out test and the inclined plate sliding test were conducted to measure the tangential and normal adhesion forces. To explore the underlying mechanisms influencing adhesion, measurements of the contact angle were performed.

3. RESULTS AND DISCUSSION

3.1 EFFECT OF ELECTROVALENCY

Under the influence of the $MgCl_2$ additive, normal adhesion initially increased and then decreased with rising water content, resulting in a bell-shaped curve (Fig. 1a). As the $MgCl_2$ additive content increased, the peak in normal adhesion shifted to the left. Tangential adhesion decreased with increasing water content, reaching a minimum value of 2 N (Fig. 1b). Additionally, the frictional coefficient ultimately decreased to approximately 0.3 as water content increased (Fig. 1c).

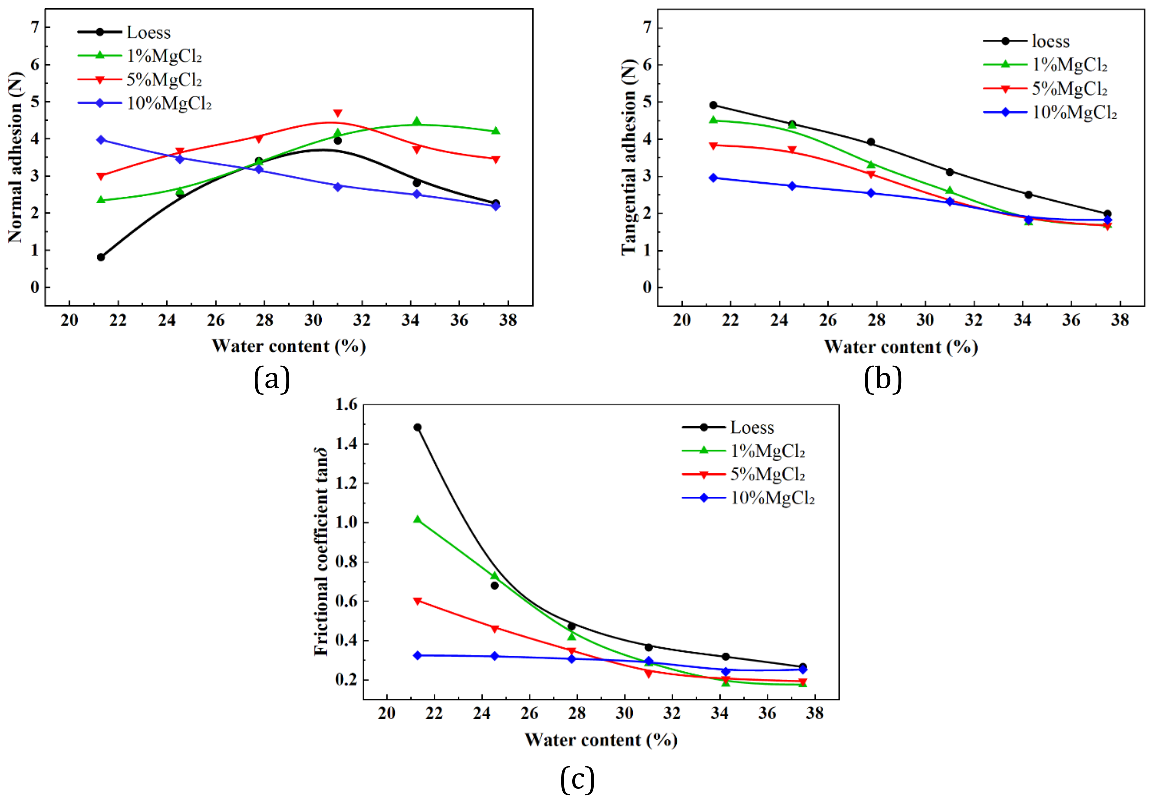


Figure 1: Measured adhesions and frictional coefficients influenced by $MgCl_2$ additive: (a) relationship of normal adhesion vs. water content, (b) relationship of tangential adhesion vs. water content, and (c) relationship of frictional coefficient vs. water content

The normal adhesion peaked at about 4.4 N as the water content reached 37% under the influence of a 1% Na_2SO_4 additive (Fig. 2a). This peak increased to 5.4 N and 6 N, respectively, when the water content remained at the same level, but the additive concentration was raised to 5% and 10%. Tangential adhesion declined to a range of 2.9-3.2 N when the water content rose to 37% (Fig. 2b), while the frictional coefficient decreased to 0.3 with increasing water content (Fig. 2c).

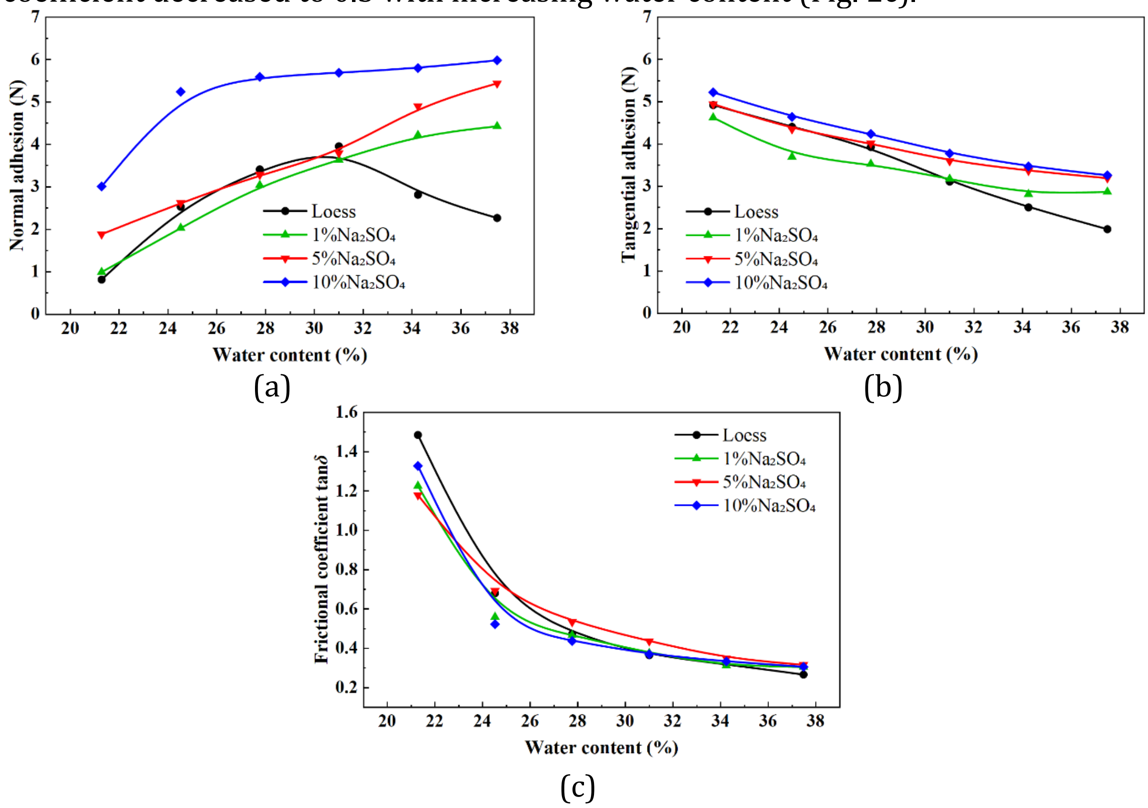


Figure 2: Measured adhesions and frictional coefficients influenced by Na_2SO_4 additive: (a) relationship of normal adhesion vs. water content, (b) relationship of tangential adhesion vs. water content, and (c) relationship of frictional coefficient vs. water content

These results demonstrated that cations such as Mg^{2+} reduced the Debye length, thereby decreasing the absolute value of electrokinetic potential (below 25 mV). Under these conditions, fluid viscosity dominated over capillary tension, triggering adhesion at the soil–metal interface. In contrast, anions such as SO_4^{2-} increased the Debye length, increasing the absolute value of electrokinetic potential (above 25 mV).

3.2 EFFECT OF ENVIRONMENTAL PH

Tunneling in northwest China significantly increases exposure to alkaline environments, while extensive metallurgical activities can transform the environment into acidic conditions. Normal adhesion peaked at 4.3 N when the water content ranged from 28% to 31% under the influence of a 1% HCl additive (Fig. 3a). This peak, reaching approximately 7.5 N, shifted to the right when exposed to a 5% HCl additive. Additionally, tangential adhesion declined to 2.3 N when the water content reached 37% with a 1% HCl additive and further decreased to 1.4 N under a 5% HCl additive (Fig. 3b). The normal adhesion peaked at 2 N when the water content reached 31% under the influence of a 1% NaOH additive. This peak, reaching 1.6 N, shifted to the right when a 5% NaOH additive was applied. Additionally, tangential adhesion declined to 0.8 N at 37% water content with a 1% NaOH additive and further decreased to 1.1 N with a 5% NaOH additive.

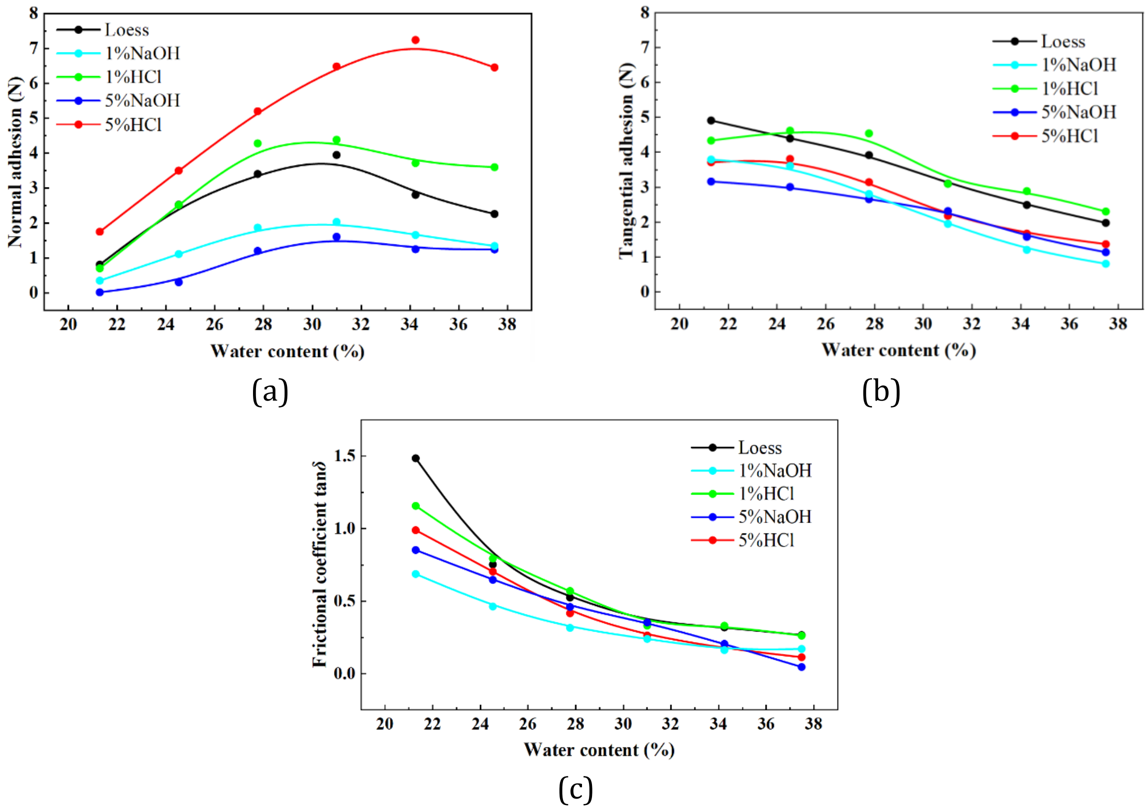


Figure 3: Measured adhesions and frictional coefficients influenced by environmental pH: (a) relationship of normal adhesion vs. water content, (b) relationship of tangential adhesion vs. water content, and (c) relationship of frictional coefficient vs. water content

3.3 EFFECT OF ELECTROOSMOSIS FLOW

Electroosmosis was employed to prevent the development of conditions that enhance adhesion potential at the soil–metal interface. The addition of NaCl proved effective in reducing adhesion, with the reduction becoming more pronounced as water content increased, as evidenced by electroosmosis flow toward the cathode. Results relevant to NaCl addition are not included for brevity. Unlike the NaCl additive, the $MgCl_2$ additive was effective in reducing adhesion only when the water content was high (Fig. 4). Notably, under the influence of a 10% $MgCl_2$ additive, electroosmosis flow toward the cathode was not observed at either high or low water content. Instead, electroosmotic flow toward the anode was measured, resulting in a decrease in normal adhesion and an increase in tangential adhesion. This reversed electroosmosis flow caused the soil–metal interface to become dry and rough.

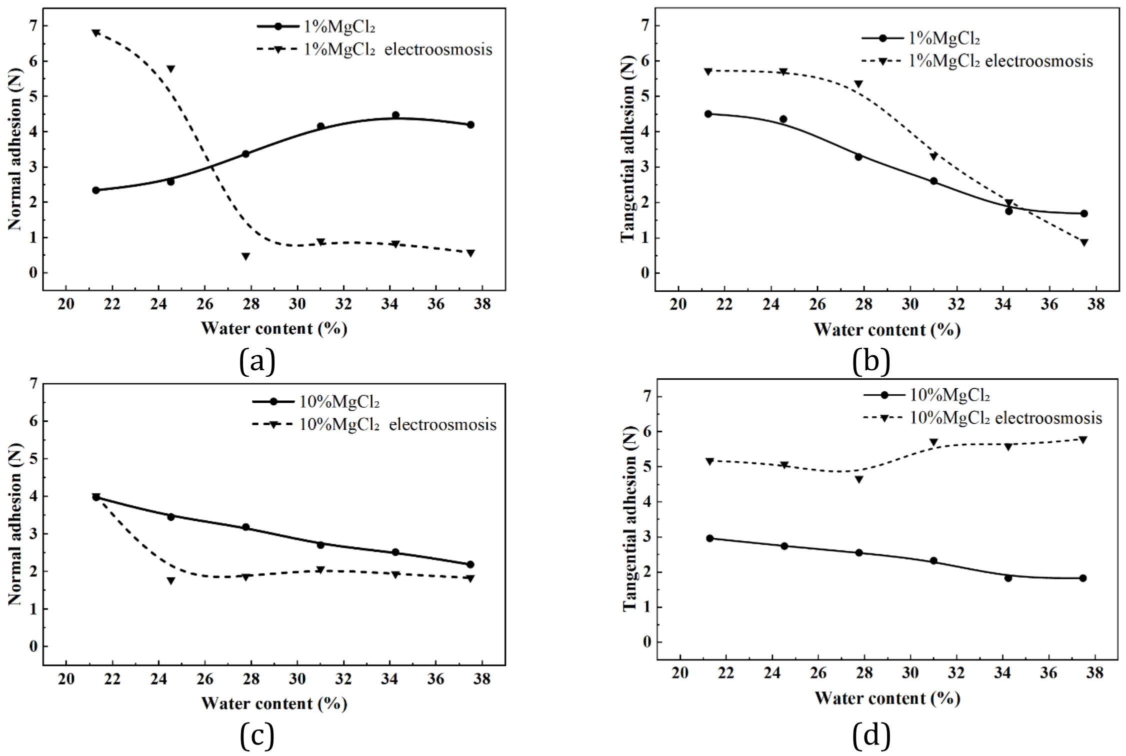


Figure 4: Measured adhesions and frictional coefficients influenced by electroosmosis flow: (a) relationship of normal adhesion vs. water content with 1% $MgCl_2$ additive, (b) relationship of tangential adhesion vs. water content with 1% $MgCl_2$ additive, (c) relationship of normal adhesion vs. water content with 10% $MgCl_2$ additive, and (d) relationship of tangential adhesion vs. water content with 10% $MgCl_2$ additive

Reversed electroosmosis flow was more frequently observed under the influence of the $AlCl_3$ additive. With a 1% AlCl3 additive, reversed electroosmosis flow was measured except when the water content exceeded 24% (Fig. 5). Normal adhesion peaked at 8.3 N when the water content was 21% but remained below 1 N when the water content reached 24% or higher. Under the influence of a 10% $AlCl_3$ additive, normal adhesion peaked at 2.4 N when the water content was 21% and decreased to below 1 N when the water content reached 31% or higher. Tangential adhesion, in turn, exceeded levels observed prior to electroosmosis under these conditions.

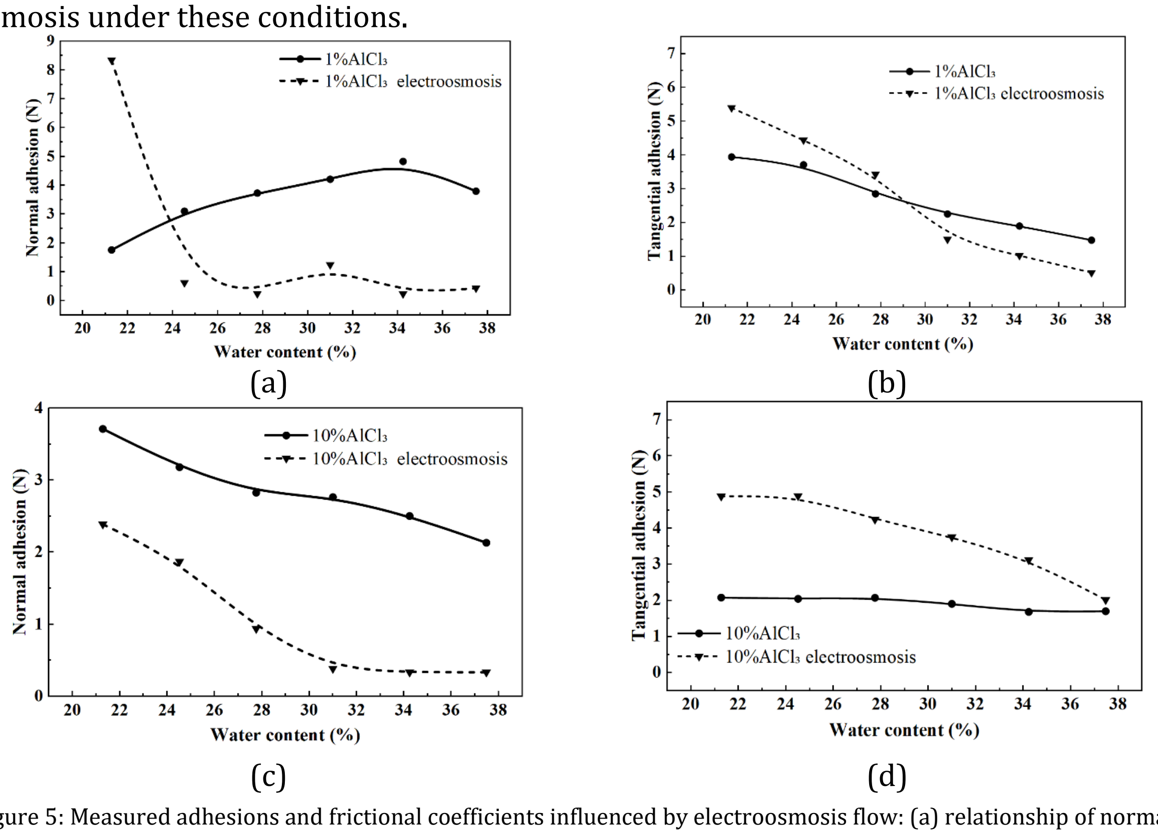
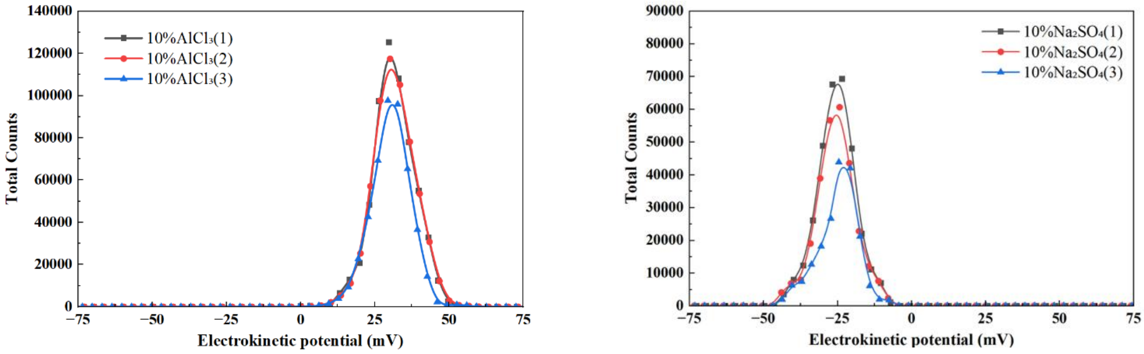


Figure 5: Measured adhesions and frictional coefficients influenced by electroosmosis flow: (a) relationship of normal adhesion vs. water content with 1% $AlCl_3$ additive, (b) relationship of tangential adhesion vs. water content with 1% $AlCl_3$ additive, (c) relationship of normal adhesion vs. water content with 10% $AlCl_3$ additive, and (d) relationship of tangential adhesion vs. water content with 10% $AlCl_3$ additive

3.4 UNDERLYING MECHANISMS

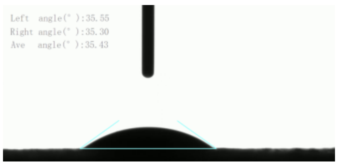
This section aims to deepen the fundamental understanding of the relation of electrochemical properties with loess adhesion, thus elucidating the underlying mechanisms. Al^{3+} reduced the Debye length and decreased the absolute value of electrokinetic potential (to below 25 mV) (Fig. 6a). As a consequence, fluid viscosity became dominant over capillary tension, leading to an increased potential for adhesion at the soil–metal interface. SO_4^{2-} was expected to increase the Debye length and raise the absolute value of electrokinetic potential. However, after ionization, SO_4^{2-} reduced electrostatic repulsion by altering the distribution of surface charges. Consequently, the Debye length was reduced, and the absolute value of electrokinetic potential was further decreased (Fig. 6b).



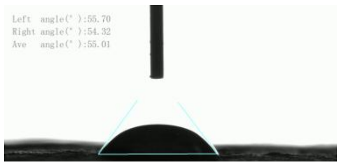
(a) (b)

Figure 6: Measured electrokinetic potentials influenced by electrovalency: (a) AlCl3 additive and (b) Na2SO4 additive

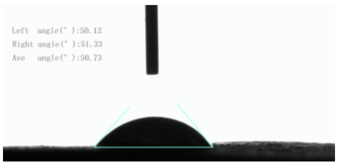
The acidic environment reduced the Debye length, decreasing the absolute value of electrokinetic potential. As a result, the formation of a viscous water film at the soil–metal interface was promoted. This was corroborated by measurements of contact angles lower than those of pure loess (35.43 vs. 50.73), indicating higher fluid viscosity and lower capillary tension (Figs. 7a and 7c). The alkaline environment increased the Debye length, leading to a higher absolute value of electrokinetic potential. Consequently, the absence of viscous fluid at the interface reduced the potential for adhesion between the soil and metal surfaces. Contact angles higher than those of pure loess were measured (55.01 vs. 50.73), corresponding to lower fluid viscosity and higher capillary tension (Figs. 7b and 7c).



(a)



(b)



(c)

Figure 7: Measured contact angles influenced by environmental pH: (a) acidic environment, (b) alkaline environment, and (c) pure loess

A substantial reduction in both normal and tangential adhesion was observed in samples mixed with cations and anions, except in the presence of $MgCl_2$ and $AlCl_3$ additives. The increase in adhesions was ascribed to 'reversed' electroosmosis flow, wherein the high electrovalency of the cations reversed the surface charges from negative to positive. This unusual charge reversal was further supported by photographic evidence (Fig. 8), which appeared dry and exhibited enhanced surface roughness. Using high molarities of $AlCl_3$ not only led to the compression of the diffuse double layer but also reversed the electroosmosis flow direction. Also based on the Coulomb's law, the compression of diffuse double layer resulted in a minimum electrostatic force at the soil–metal interface, primarily due to reduced repulsive forces and an increased contribution from adsorptive Van der walls forces.

(a) (b)

Figure 8: Photographic evidence: (a) electroosmosis flow and (b) 'reversed' electroosmosis flow

4. CONCLUSIONS

This study investigated the electrochemical reduction of loess adhesion on shield machine cutting tools. Based on the results and discussion, some main conclusions can be drawn as follows:

Cations with high electrovalence, such as Mg^{2+} and Al^{3+}, were found to reduce the Debye length and decrease the absolute value of electrokinetic potential (to below 25 mV). The observed leftward shift in the peak of normal adhesion toward the plastic limit indicated the formation of a viscous water film at the soil–metal interface, thereby increasing the potential for adhesion at the interface. In contrast, the influence of anions generally resulted in a reduction of both normal and tangential adhesions, except in the case of SO_4^{2-}. SO_4^{2-} diminished electrostatic repulsion and decreased the absolute value of electrokinetic potential (to below 25 mV), leading to an unexpected increase in both normal and tangential adhesions.

Acidic pH conditions were found to reduce the Debye length and the absolute value of electrokinetic potential. This, in turn, elevated the potential for adhesion at the interface. Conversely, alkaline pH increased the Debye length, resulting in a higher absolute value of electrokinetic potential. Notably, contact angles higher than that of pure loess corresponded to lower fluid viscosity and higher capillary tension, providing further evidence in support of the argument.

Electroosmosis was demonstrated to be effective in reducing both normal and tangential adhesion, except in the presence of $MgCl_2$ and $AlCl_3$ additives. When $MgCl_2$ and $AlCl_3$ were introduced, adhesion values exceeded those measured prior to electroosmosis treatment, most likely due to the development of 'reversed' electroosmosis flow. This phenomenon resulted in the compression of the diffuse double layer, most likely due to reduced repulsive forces and an increased contribution from adsorptive Van der walls forces.

5. ACKNOWLEDGEMENTS

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