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Effects of Dry Density and Moisture Content on the Kaolin–Brass Interfacial Shear Adhesion

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Abstract: Kaolin clay, with its consistent properties, fine particle size, high surface area, and extensive historical use, stands out as a reliable choice for laboratory research. This study aims to assess the interface shear adhesion behaviour between compacted clay and a metallic surface. For this purpose, a new testing approach was developed. The proposed method is simple, requires neither advanced equipment nor specialised test procedures, and, thus, represents an improvement over existing practices in this field. The experimental program focuses on determining the interface shear adhesion strength between reconstituted kaolin clay and a metallic surface. The kaolin clay testing specimens were dynamically compacted at various energy levels and moisture contents. The results indicate that the optimum moisture content is 30%, which provides the highest density to the sample and divides the compaction curve into dry and wet sides. Furthermore, the results demonstrate that the interface shear adhesion strength increases with the clay's dry density. Conversely, there is a significant decrease in strength as the moisture content specifically rises on the wet side of the compaction curve. The adhesion behaviour was also attributed to matric suction, where high suction enhanced interfacial adhesion, while low suction weakened bonding and diminished adhesion. Additionally, this study presents a unique three-dimensional contour graph illustrating the combined effects of dry density and moisture content on the interfacial adhesion.

Keywords: dry density; moisture content; kaolin; brass; interface; shear adhesion

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1. Introduction

Interfacial adhesion refers to the ability of soil particles to adhere to the interface of other materials in the presence of water [1]. The system of soil adhesion comprises three elements: soil, solid surfaces, and their interface [2]. An example of interfacial adhesion commonly encountered is between clay and metal. It is important to differentiate between soil adhesion and soil cohesion, as shown in Figure 1, where the former involves soil particles adhering to other materials, and the latter refers to soil particles sticking to each other [3].

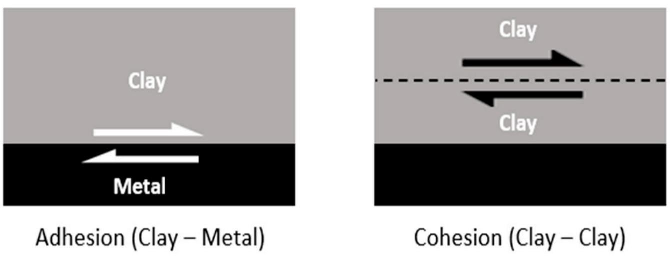

Figure 1. Illustration of adhesion and cohesion of soil.

There are two types of soil adhesion: normal adhesion and shear (tangential) adhesion [2]. The applied load is the factor that determines the adhesion type. The normal adhesion is accommodated with normal tensile load, and the shear adhesion is accommodated with shear load, as shown in Figure 2.

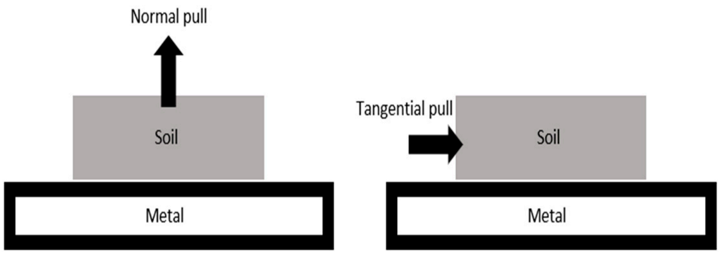

Figure 2. The adhesive tensile strength (normal pull) and the adhesive shear strength (tangential pull).

Adhesion behaviour at interfaces is influenced by various factors, including soil properties, material properties, interface properties and test conditions, as shown in Figure 3 [4,5]. Soil properties affecting interfacial adhesion include soil composition, grain size distribution, porosity, specific surface area (SSA), moisture content, water salinity, matric suction, plasticity, consistency and cohesion [4–6]. According to Zhang and Sang [7], shear adhesion and moisture content exhibit a parabolic relationship, as defined in Equation (1).

$$I_c = \frac{LL - MC}{PI} \tag{1}$$

where I_c is the consistency index of the soil, LL is the liquid limits, MC is the moisture content, and PI is the plasticity index. Thus, there is a relationship between the consistency index and shear adhesion, which assists in understanding the behaviour of clay adhesion [8]. Material properties that influence interfacial adhesion include the contact area, applied normal load, and roughness of the surface area [9]. Testing conditions, such as the contact time at the soil–material interface, rate of loading, humidity, and temperature of the interface surface, also play a significant role in affecting the behaviour and value of interfacial soil adhesion [6,10].

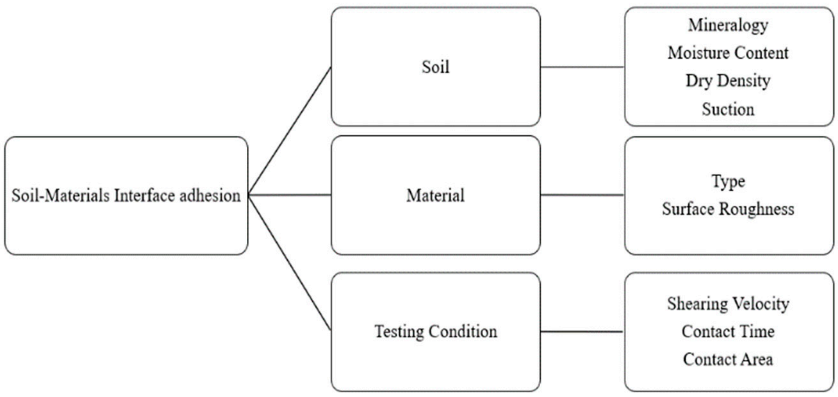

Figure 3. Factors affecting interfacial soil adhesion.

The interfacial soil adhesion derives importance from its applications in geotechnical engineering and agriculture, where it can pose potential challenges. For example, pile foundations, as shown in Figure 4, may encounter stickiness issues during the digging process [11], and the cutter head of a tunnel boring machine (TBM) can experience clogging problems at the interface due to interfacial soil adhesion [12–14].

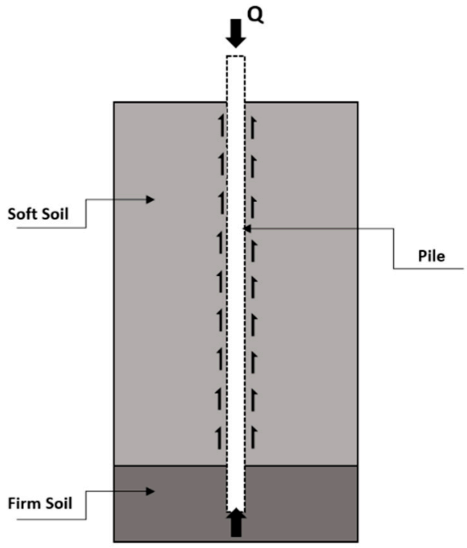

Figure 4. Pile Foundation and stickiness during digging.

These practical applications of interfacial soil adhesion can lead to unexpected cost implications. Additionally, soil sticking to agricultural machines during harvesting can result in high energy consumption and reduced work efficiency [6,8]. Therefore, it is crucial to investigate the behaviour of soil adhesion with other materials.

Several studies have employed different methods to measure soil adhesion; however, there is no specific method or device exclusively designed for soil adhesion measurement [3]. Soil adhesion can be measured in the laboratory using pull-out tests [12], piston separation tests [15] and shear plate tests [16]. Fountaine [1] used a specialised apparatus to measure normal adhesion for loam clay and sandy clay under the influence of water surface tension. Their study revealed that moisture content and material type have an impact on soil adhesion. Thewes and Burger [12] utilised pull-out tests to investigate clogging issues in TBMs, where normal soil adhesion occurs. It was found that clay minerals and soil consistency index (I_c) affect normal adhesion. Azadegan and Massah [17] designed a dedicated instrument to measure normal adhesion between clay and steel. Their study focused on the effect of temperature on adhesion and demonstrated that temperature influences soil adhesion. Mirjavan [15] employed a piston separation device to measure the normal adhesion of soil to metal. The study investigated wetness levels of montmorillonite clay and revealed that wetness is a significant influencing factor. Burbaum and Sass [18] used pull-out load or separation tests to investigate normal adhesion between clay and steel surfaces, finding that adhesion is influenced by the soil consistency index. Zumsteg and Puzrin [16] employed a plate apparatus to examine the clogging issue occurring at the interface between clay and TBM machines during tunnelling. They identified tangential adhesion as the main factor contributing to soil stickiness and clogging issues. This paper aims to investigate the behaviour of shear adhesion at the interface between kaolin clay and the internal surface of a brass mould. This study involves testing thirty compacted kaolin samples with different moisture contents and compaction energy levels (dry density). To conduct the experiment, a new simple test method was developed to measure interfacial shear adhesion between kaolin and brass. The testing methodology introduced in this research study represents a pioneering approach by employing conventional soil testing equipment for evaluating interface shear adhesion. This stands in contrast to previous investigations, wherein specialised testing apparatus, which may not be readily accessible in commercial laboratories, were utilised.

2. Materials and Methods

2.1. Materials

The interface adhesion test conducted in this study involved using kaolin clay as the testing material, sourced from "Scott Chemical Australia Pty Ltd." (Cheltenham, Australia) in Melbourne, Australia. Kaolin clay is commonly used in geotechnical engineering studies due to its availability and representative properties. Different clay compositions can influence various properties, such as shrinkage, plasticity, and strength. These changes in properties can, in turn, impact the experiment results by altering the clay's behaviour under various conditions. In this experiment, we maintained a consistent mineral composition among samples to ensure reliable results. The mineral composition of the kaolin, specified on the clay bag, is shown in Table 1.

Table 1. Mineral composition of the kaolin.

Mineral	Mass Percentage
Kaolinite	83.7
Muscovite	14.0
Quartz	2.3

To further characterize the kaolin clay, Table 2 presents the geotechnical properties that were examined during this study. These properties include parameters such as moisture content, dry density, shear strength, and compaction energy. Understanding the geotechnical properties of the soil is crucial for assessing its behaviour under different loading and moisture conditions.

Table 2. Engineering properties of the used soil (kaolin).

Properties	Values
Specific gravity (G_s)	2.58
LL (%)	74
PL (%)	32
PI (%)	42
Cation exchange capacity (CEC) (meq/100 g)	0.075
Total surface area (m^2/g)	20
Surface charge density ($\mu C/m^2$)	0.36
Silicate SiO_2	45.2
Aluminium Al_2O_3	38.8

Additionally, Figure 5 shows the particle size distribution of the kaolin clay. This distribution illustrates the relative proportions of different particle sizes present within the soil sample. The particle size distribution plays a significant role in determining the mechanical and hydraulic properties of the soil, affecting factors such as compaction behaviour, permeability, and shear strength.

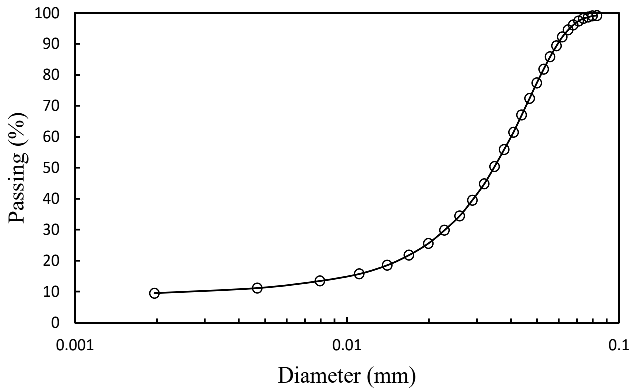

Figure 5. Particle size distribution of kaolin.

2.2. Preparation

To carry out the interfacial adhesion test, 30 different samples were prepared. The prepared samples produced different moisture contents and dry density conditions. The percentage of moisture was between 10 and 50%. The kaolin samples were compacted at different compaction energy levels using a series of blows ranging from 15 to 55 blows to achieve the minimum and maximum dry density at different moisture levels, as listed in Table 3. The soil was compacted in the mould in three equal layers of almost 43 mm. The same amount of energy was applied to each layer. The moisture content used was regular tap water. After adding varying amounts of moisture to the soil samples, each sample was placed in a sealed plastic bag and kept overnight for moisture equalisation.

Table 3. The amount of water content and number of blows used in the experiment.

MC (%)	10	20	25	30	40	50
Number of blows	15	15	15	15	15	15
	25	25	25	25	25	25
	35	35	35	35	35	35
	45	45	45	45	45	45
	55	55	55	55	55	55

2.3. Approach

After the soil had been compacted in the compaction mould, the next step was to test the interfacial shear adhesion with a loading machine. This approach enabled the interfacial shear strength between the compacted soil and the brass mould to be evaluated.

To prepare the compaction mould for testing, it was inverted, and the mould base was removed. This allowed the compacted soil to be extruded from the mould, exposing the surface that was in contact with the brass mould during the shear adhesion test. This setup ensured a consistent interface between the soil sample and the mould and allowed accurate measurements of shear adhesion.

The loading machine was then utilised to apply a displacement-controlled load to the compacted soil, compressing it out of the mould. The loading machine's mechanism and setup are illustrated in Figure 6, providing a visual representation of the process. The displacement rate employed in this study was 5.0 mm/min. This rate ensured a controlled and uniform compression of the compacted soil, allowing precise measurements and reliable data acquisition.

By subjecting the compacted soil to a displacement-controlled load, the loading machine simulated the conditions under which the soil is subjected to external forces or loading in real-world applications. This enabled the shear adhesion strength between the soil and the mould to be evaluated, providing valuable insights into the stability of the soil and its interaction with surrounding materials.

The utilisation of a displacement-controlled load and a consistent loading rate ensured standardised testing conditions, enabling accurate comparisons between different soil samples and variations in compaction parameters. The data obtained from these tests contributed to a better understanding of soil behaviour and its response to external loads and helped in the planning and implementation of various engineering projects.

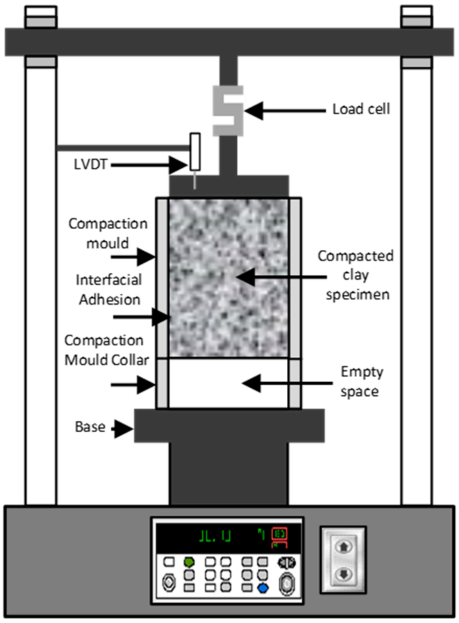

Figure 6. Schematic diagram of the apparatus and the test setup.

The testing process involved shearing the soil against the internal surface of the mould by applying a vertical load. To ensure that the machine load did not cause additional compression on the compacted specimen, which could have potentially damaged it by excessive squeezing, it is crucial for the movement of the compacted specimen to precisely match the loading displacement. Throughout the loading process, both the displacement and the load are accurately recorded and plotted. The peak of the load-displacement curve shows the maximum adhesion capacity of the interface between the compacted kaolin and the inner wall of the brass mould, as shown in Figure 7. The soil–mould interface adhesion can be determined using Equation (2):

$$\alpha = \frac{P}{A} \tag{2}$$

where α is the interfacial adhesion (kPa), P is the peak load (kN), and A is the internal surface of the mould (m^2).

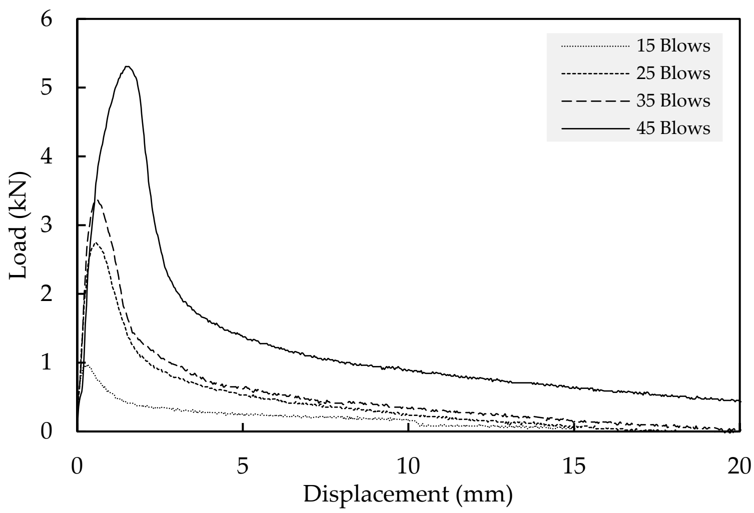

Figure 7. Kaolin adhesion at 30% optimum moisture and varying compaction levels.

3. Results

3.1. Compaction Curve

The compaction curve displayed in Figure 8 provides valuable insights into the behaviour of kaolin under different compaction energies and moisture contents. By examining the curve, the relationship between dry density, compaction energy, and moisture content can be observed.

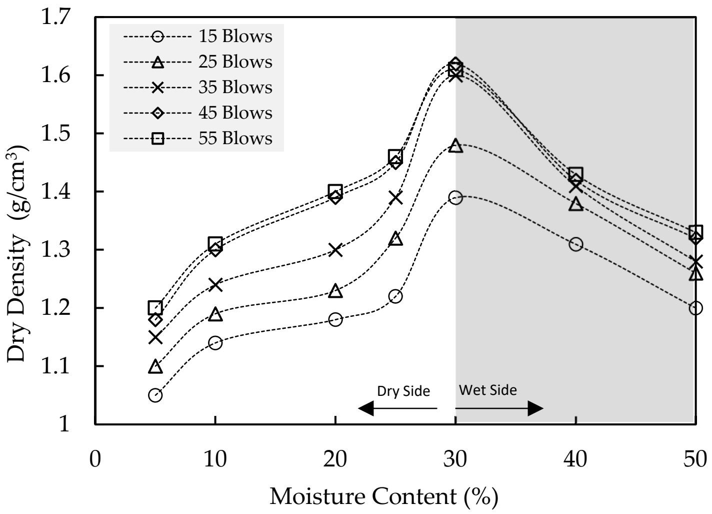

Figure 8. Compaction curve of kaolin at different compaction levels.

The compaction curve shows the variations in dry density as a function of compaction energy, represented by the number of blows (15, 25, 35, 45 and 55 blows) and the moisture content in the range from 10 to 50%. Each combination of compaction energy and moisture content corresponds to a specific point on the compaction curve. At 15 blows, the dry density increases from 1.14 at 10% MC to a peak of 1.39 at 30% MC, then descends to 1.20 at 50% MC. At 55 blows, the dry density ranges from 1.31 at 10% MC to 1.61 at 30% MC, decreasing to 1.33 at 50% MC. The peaks observed on the compaction curve indicate the optimum moisture content (OMC) of the kaolin, which is at 30% moisture content in all cases studied. The OMC represents the moisture content at which the kaolin reaches its maximum dry density during the compaction process. This optimum moisture content is important to achieving the desired compaction properties and overall soil performance. The OMC effectively divides the compaction curve into two distinct sides: the dry side and the wet side. The basis for dividing the compaction curve is primarily to categorize soil adhesion behaviour into two stages: one strongly affected and the other weakly affected. The moisture content ranging from 10 to 30% represents the dry side, while the range of 30 to 50% represents the wet side.

3.2. Dry Density

The relationship between dry density and interfacial shear adhesion at the dry side is presented in Figure 9. It is observed that there is a linear relationship between dry density and shear adhesion, wherein an increase in dry density leads to an increase in shear adhesion at each moisture content value. This finding highlights the importance of compaction in influencing interfacial adhesion behaviour.

Detailed analysis revealed that the impact of dry density on shear adhesion is more pronounced at the dry side of the compaction curve compared to the wet side. When kaolin clay is compacted to a greater extent within the dry side, the soil particles come closer to each other, resulting in creating a denser surface area. At an MC of 10%, adhesion values range significantly from approximately 23.6 to 124 kPa across varied dry densities. This densification of the soil enhances the contact area between kaolin and the brass mould. Consequently, the interfacial shear adhesion is strengthened due to the increased contact between the soil particles and the mould surface. It should be noted that the extent of the increase in dry density is dependent on the moisture content. In other words, the effect of the dry density on interfacial shear adhesion varies with the moisture content.

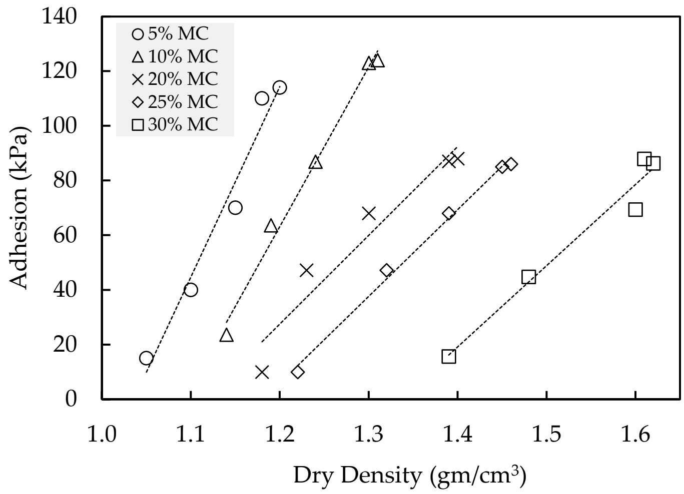

Figure 9. Dry density versus interfacial adhesion on kaolin at different moisture content levels.

3.3. Moisture Content

Figure 10 provides an insight into the behaviour of interfacial shear adhesion in compacted kaolin under the influence of moisture content. It has been observed that with a low moisture content ranging from 5 to 10% MC, the adhesion increases. Specifically, at 10% MC, it shows the highest adhesion among the different levels of compacted kaolin on the dry side. However, when the moisture content approaches the OMC, especially between 20 and 30%, increasing the moisture content has a slight effect on adhesion, which can be considered negligible.

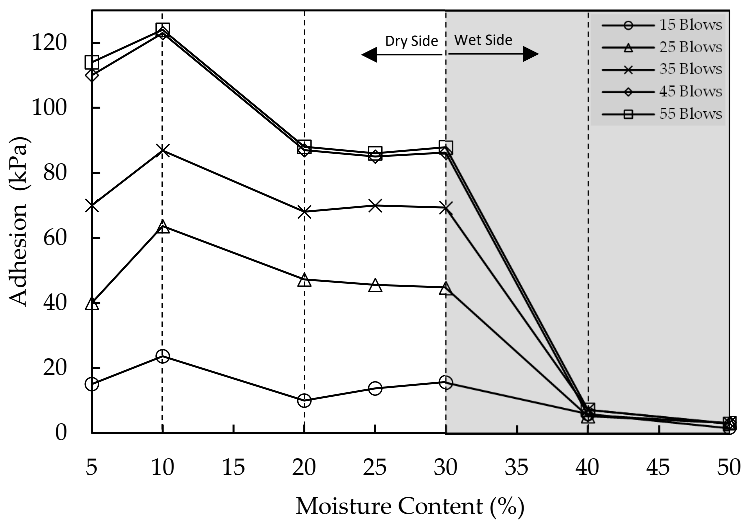

Figure 10. Interface adhesion of kaolin at different moisture contents and densities.

The behaviour of the unaffected area on the dry side can be explained by considering the maximum dry density of the soil at that point. At the OMC, the soil reaches its maximum dry density, resulting in a dense contact area between the kaolin and the mould surface. This dense interface contributes to the formation of the strongest interfacial adhesion. Consequently, there is a balanced effect between dry density, which typically improves adhesion, and moisture content, which often decreases adhesion. On the other hand, on the wet side, which is characterised by extreme moisture content and a high degree of saturation, a significant decrease in interfacial shear adhesion is observed. At the highest moisture content of 50%, the interface adhesion becomes null. This behaviour can be attributed to the detrimental effects of excessive moisture content and saturation on the interfacial adhesion properties of the kaolin.

3.4. Coupling Effect of Dry Density and Moisture Content

Figure 11 presents a novel three-dimensional graph showing the coupling effect of dry density and moisture content on the interfacial shear adhesion between kaolin and a brass mould. This graph provides a comprehensive visualisation of the relationship between these two parameters and their influence on shear adhesion. For the studied case, the light grey shaded area represents the possible shear adhesion values in relation to moisture content and dry density. The diagram of the contour lines provides valuable insights. It shows that at constant dry density, shear adhesion tends to decrease as moisture content increases. This relationship suggests that higher moisture content generally leads to a reduction in interfacial adhesion between kaolin and the brass mould.

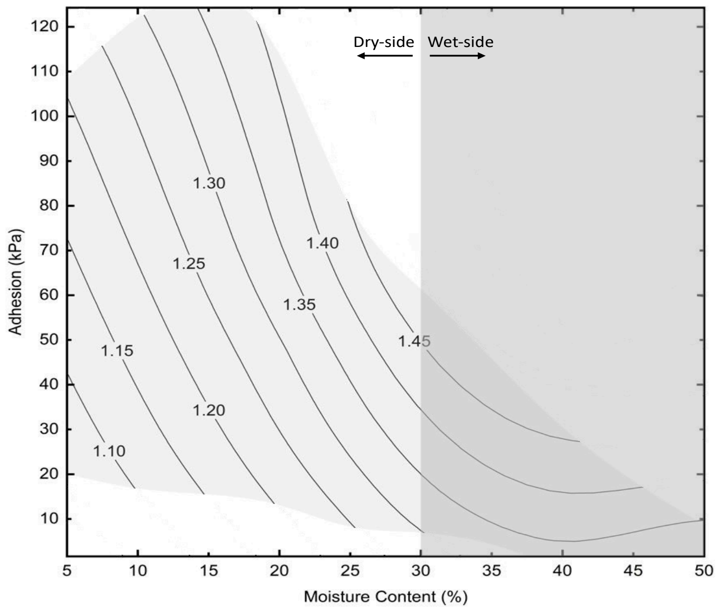

Figure 11. Three-dimensional contour graph of the effects of dry density and moisture content on shear adhesion of kaolin.

Figure 12 represents the adhesion change rate (*ACR*), which is the rate at which the adhesion value changes with variations in dry density at different water content levels. As dry density is a function of the *ACR*, it is important to note that the *ACR* of shear adhesion reduction varies with dry density and can be calculated using Equation (3):

$$ACR = \frac{\alpha_2 - \alpha_1}{\rho_{d2} - \rho_{d1}} \quad (3)$$

where *ACR* is the adhesion change rate; α_2 and α_1 are the final and initial adhesion values, respectively; and ρ_{d2} and ρ_{d1} are the final and initial dry density values, respectively. The information provided by these contour lines allows a more detailed understanding of the interaction between dry density, moisture content, and interfacial shear adhesion. The graph shows that changes in these parameters affect the adhesion behaviour of the kaolin. This understanding can help to optimize compaction processes and control moisture content to achieve desired shear adhesion properties.

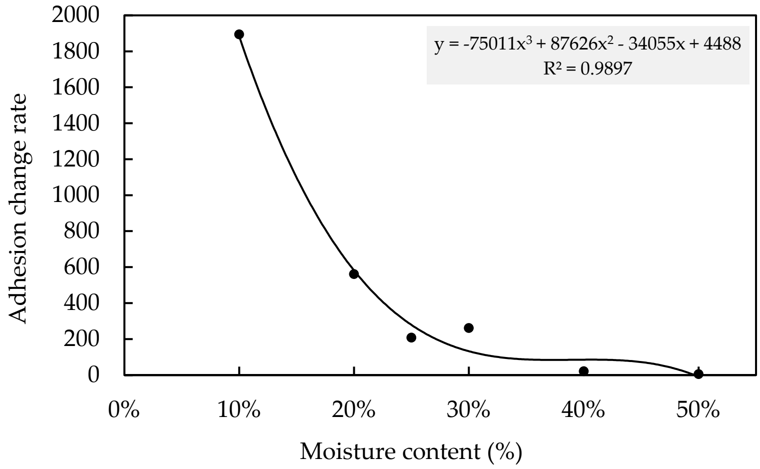

Figure 12. The relationship between the adhesion change rate and moisture content.

4. Discussion

The interfacial adhesion behaviour between kaolin and brass can vary depending on whether it is observed on the dry or wet side of the compaction curve. The compaction curve is a graph showing the relationship between compaction pressure and the resulting density or porosity of a material. An analysis of the interfacial adhesion behaviour on either side of the compaction curve can provide insights into the mechanisms that control the interaction between kaolin and brass.

In Alshameri's [19] experiment, he used a mixture of sand and kaolin at different percentages. In his study, a mixture of 80% sand and 20% kaolin yielded the highest dry density, with an OMC of 12%. In contrast, this experiment exclusively used kaolin clay and achieved the highest dry density with an OMC of 30%. This paper presents a wide range of dry density samples, achieved by considering various numbers of blows at different moisture contents, as shown in Table 4.

Table 4. Summary of interfacial adhesion behaviour for dry and wet sides.

Number of Blows	MC (%)	ρ_d (g/cm^3)	Su (pF)	α (kPa)
15	5	1.05	5.00	15.00
	10	1.14	4.70	23.59
	20	1.18	4.40	9.92
	25	1.22	4.32	13.66
	30	1.39	3.67	15.62
	40	1.31	3.05	6.02
	50	1.20	2.00	1.63
25	5	1.10	5.00	40.00
	10	1.19	4.71	63.60
	20	1.23	4.43	47.17
	25	1.32	4.41	45.55
	30	1.48	3.82	44.73
	40	1.38	3.19	5.37
	50	1.26	2.17	3.25

Table 4. *Cont.*

Number of Blows	MC (%)	ρ_d (g/cm^3)	Su (pF)	α (kPa)
35	5	1.15	5.00	70.00
	10	1.24	4.72	86.86
	20	1.30	4.45	68.00
	25	1.39	4.44	69.95
	30	1.60	3.84	69.30
	40	1.41	3.40	7.32
	50	1.28	2.29	3.09
45	5	1.18	5.00	110.00
	10	1.30	4.75	123.00
	20	1.39	4.48	87.00
	25	1.45	4.20	85.00
	30	1.62	3.89	86.21
	40	1.42	2.83	5.69
	50	1.32	2.20	3.20
55	5	1.20	5.00	114.00
	10	1.31	4.66	124.00
	20	1.40	4.50	88.00
	25	1.46	4.45	86.00
	30	1.61	4.10	87.84
	40	1.43	3.60	7.32
	50	1.33	2.10	3.00

4.1. Mechanism of Adhesion on the Dry Side

It has been observed that on the dry side of the compaction curve, interfacial adhesion increases, with higher dry density values at any moisture content. Conversely, adhesion decreases with increasing moisture content. On the dry side of the compaction curve, where the pressure is relatively low, the interfacial adhesion behaviour between kaolin and brass is mainly influenced by physical interlocking and mechanical friction. When pressure is applied, the kaolin particles tend to encounter the brass surface, creating points of contact and interlocking. This physical interlocking creates a certain level of adhesion between the two materials. In addition, the roughness and surface irregularities of the brass surface can contribute to adhesion. The kaolin particles can fill in the gaps and irregularities on the brass surface, resulting in a larger contact area and stronger adhesion.

4.2. Mechanism of Adhesion on the Optimum Moisture Content

At the OMC point on the compaction curve, where pressure is at its peak, the adhesion behaviour between kaolin and brass undergoes marked changes. Moisture content plays a crucial role in influencing the underlying adhesion mechanisms in that specific region. However, despite the observed changes, it should be noted that the interfacial adhesion at the OMC is not the highest. The adhesion between kaolin and brass weakens with increasing moisture content, demonstrating the negative influence of increased moisture levels on the strength of interfacial adhesion.

4.3. Mechanism of Adhesion on the Wet Side

On the wet side of the compaction curve, the presence of excessive moisture content can adversely affect the bonds between individual kaolin particles. The water essentially acts as a lubricant, reducing friction and interlocking between the particles. This weakens the bond between the particles, resulting in a significant decrease in the overall adhesion strength at the interface. However, low moisture content (5–10% MC) in the sample, as indicated by the results, shows an increase in adhesion. This can be explained by the fact that a slight increase in the moisture content increases the dry density, thereby increasing the contact surface, which leads to higher interfacial adhesion. This is in compliance with Li and Zhang [20], who showed that adhesion initially increases with moisture content and then decreases.

4.4. Matric Suction Role

This complex behaviour is further explained by the matric suction effect. Figure 13 illustrates the role of matric suction in binding the kaolin particles to the inner surface of the compaction mould. On the dry side, which is characterised by low moisture content and high soil suction, interfacial bonding is strong, resulting in increased interfacial adhesion. On the other hand, on the wet side, which is characterised by high moisture content and low soil suction, interfacial bonding becomes weak and has a negligible impact on interfacial adhesion.

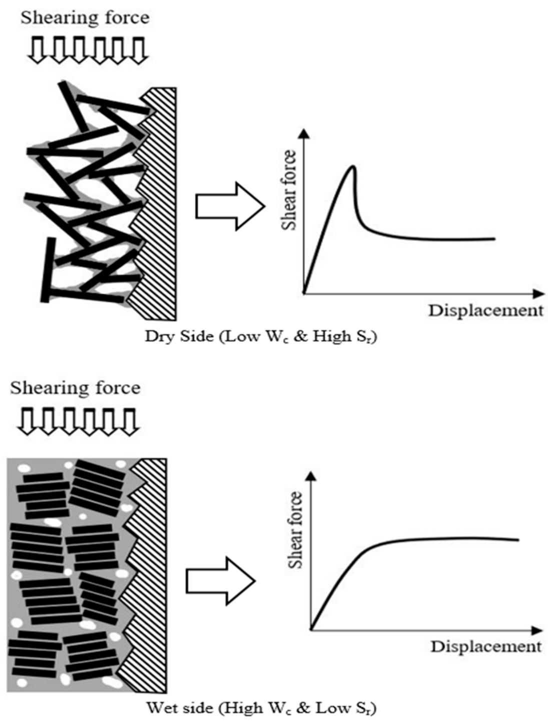

Figure 13. Interface adhesion behaviour for dry side versus wet side.

Kaolin exhibits high suction power on the dry side when moisture content is low and low suction power on the wet side when moisture content is high, as shown in Figure 14.

Figure 15 illustrates the influence of clay suction on the shear adhesion on both sides. On the dry side, where the moisture content is low and the clay is not fully saturated, the suction of clay is high and leads to high interface adhesion. Hence, the significant reduction in soil suction as moisture content increases from 10 to 30% on the dry side accelerates the loss of adhesion. On the wet side, beyond the OMC of 30%, where the moisture content is high and the clay is nearly fully saturated, the suction of clay is becoming low and leads to low interface adhesion. Hence, the low suction due to the high degree of saturation leads to a sudden failure in the interfacial adhesion. This adhesion failure is due to the combined effect of high moisture content, where the soil is fully saturated, and low suction.

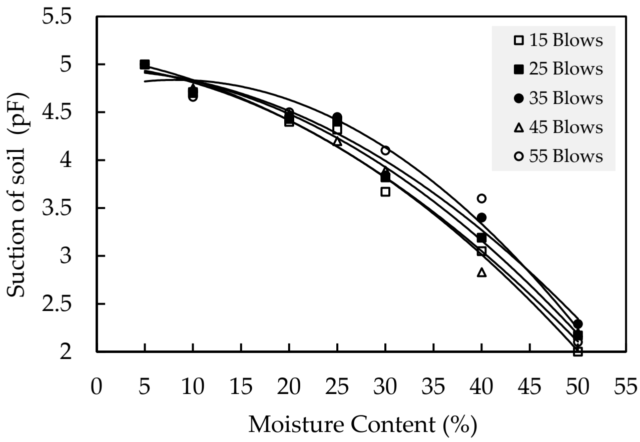

Figure 14. Behaviour of suction against the moisture content for varied compacted kaolin.

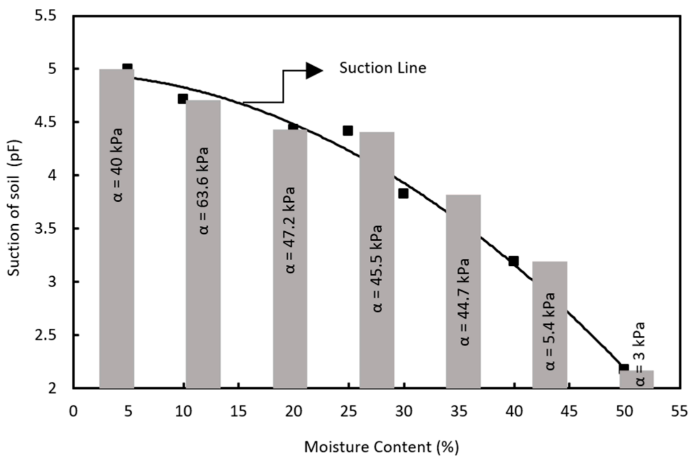

Figure 15. Influence of suction on interface adhesion of kaolin at a standard compaction of 25 blows.

4.5. Limitation

This study has some limitations that should be acknowledged and addressed in future research. Firstly, this study only used kaolin clay as the testing material, which may not represent the behaviour of other types of clay or soil mixtures. Future studies could consider different types of clay mixed with sand or recycled materials [21,22] to investigate the effect of soil composition on interfacial shear adhesion. Secondly, this study only performed the test at one displacement rate of 5.0 mm/min, which may not capture the dynamic loading conditions encountered in real-world applications. Future studies could consider different displacement rates and check the impact of loading rate on the adhesion behaviour. Thirdly, this study conducted the test at a constant room temperature of 23 °C, which may not reflect the environmental variations affecting soil properties and adhesion mechanisms. Future studies could consider the impacts of different temperatures [23] on the interfacial shear adhesion between kaolin and brass. This study focused on the impacts of dry density and moisture content on the adhesion of kaolin clay, which are important factors influencing soil performance and stability. However, other factors such as contact area, surface roughness, and contact time could also affect the interfacial adhesion behaviour and should be explored in future research.

5. Conclusions

This paper investigated the coupling effect of dry density and moisture content on the interfacial shear adhesion between kaolin clay and brass. A simple method was developed to measure the shear adhesion using a loading machine. The main findings of this study are as follows:

- With an increase in moisture content in kaolin, the dry density increases until it reaches a maximum value and then decreases. The maximum dry density of the used kaolin is observed at an OMC of 30%.
- There is a linear relationship between dry density and shear adhesion on the dry side of the compaction curve, where higher dry density leads to higher shear adhesion due to the larger area of contact with the mould surface.
- As moisture content initially increases up to 10% MC, the shear adhesion also increases. Beyond that point, the increase in MC results in a slight decrease in adhesion on the dry side of the compaction curve up to the OMC. Beyond the OMC, on the wet side of the compaction curve, there is a significant decrease in shear adhesion.
- The adhesion behaviour can be further explained by considering the role of matrix suction. High suction on the dry side improves adhesion, while low suction on the wet side weakens adhesion.
- Future research can consider different types of soil and mixtures, as well as tests performed under various shear rates and temperatures.

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Nomenclature

I_c	Consistency index
PI	Plasticity index
PL	Plastic limit
LL	Liquid limit
α	Interfacial adhesion
ρ	Dry density
P	Peak load
A	Internal surface area of the mould
Sr	Saturation degree of clay
Su	Suction of clay
G_s	Specific gravity
OMC	Optimum moisture content
MC	Moisture content
ACR	Adhesion change rate
CEC	Cation exchange capacity
TBM	Tunnel boring machine

References

1. Fountaine, E. Investigations into the mechanism of soil adhesion. *J. Soil Sci.* **1954**, *5*, 251–263. [CrossRef]
2. Tong, J.; Ren, L.; Chen, B.; Qaisrani, A. Characteristics of adhesion between soil and solid surfaces. *J. Terramech.* **1994**, *31*, 93–105. [CrossRef]
3. Alberto-Hernandez, Y.; Kang, C.; Yi, Y.; Bayat, A. Clogging potential of tunnel boring machine (TBM): A review. *Int. J. Geotech. Eng.* **2018**, *12*, 316–323. [CrossRef]
4. Jia, X. Theoretical analysis of the adhesion force of soil to solid materials. *Biosyst. Eng.* **2004**, *87*, 489–493. [CrossRef]
5. Soni, P.; Salokhe, V.M. Theoretical analysis of microscopic forces at soil-tool interfaces: A review. *Agric. Eng. Int. CIGR J.* **2006**, *8*, 1–25.

6. Sass, I.; Burbaum, U. A method for assessing adhesion of clays to tunneling machines. *Bull. Eng. Geol. Environ.* **2009**, *68*, 27–34. [CrossRef]
7. Zhang, J.; Sang, Z.; Gao, L. Adhesion and friction between soils and solids. *Nung Yeh Chi Hsieh Hsueh Pao Trans. Chin. Soc. Agric. Mach.* **1986**, *17*.
8. Liu, P.; Wang, S.; Shi, Y.; Yang, J.; Fu, J.; Yang, F. Tangential adhesion strength between clay and steel for various soil softnesses. *J. Mater. Civ. Eng.* **2019**, *31*, 04019048. [CrossRef]
9. Bhushan, B. Adhesion and stiction: Mechanisms, measurement techniques, and methods for reduction. *J. Vac. Sci. Technol. B* **2003**, *21*, 2262–2296. [CrossRef]
10. Satomi, T.; Nihei, H.; Takahashi, H. Investigation on characteristics of soil adhesion to metallic material surface and soil animal's cuticle. In Proceedings of the 15th International Conference on Experimental Mechanics, Online, 7–9 September 2021; pp. 1–9.
11. Sladen, J. The adhesion factor: Applications and limitations. *Can. Geotech. J.* **1992**, *29*, 322–326. [CrossRef]
12. Thewes, M.; Burger, W. Clogging of TBM drives in clay–identification and mitigation of risks. In *Underground Space*; CRC Press: Boca Raton, FL, USA, 2005.
13. Atkinson, J.H.; Fookes, P.G.; Miglio, B.F.; Pettifer, G.S. Destructuring and disaggregation of Mercia Mudstone during full-face tunnelling. *Q. J. Eng. Geol. Hydrogeol.* **2003**, *36*, 293–303. [CrossRef]
14. Jancsecz, S.; Krause, R.; Langmaack, L. Advantages of soil conditioning in shield tunnelling: Experiences of LRTS Izmir. In *Challenges for the 21st Century*; A.A. Balkema: Rotterdam, The Netherlands, 1999; pp. 865–875.
15. Basmenj, A.K.; Mirjavan, A.; Ghafoori, M.; Cheshomi, A. Assessment of the adhesion potential of kaolinite and montmorillonite using a pull-out test device. *Bull. Eng. Geol. Environ.* **2016**, *76*, 1507–1519. [CrossRef]
16. Zumsteg, R.; Puzrin, A.M. Stickiness and adhesion of conditioned clay pastes. *Tunn. Undergr. Space Technol.* **2012**, *31*, 86–96. [CrossRef]
17. Azadegan, B.; Massah, J. Effect of temperature on adhesion of clay soil to steel. *Cercet. Agron. Mold.* **2012**, *45*, 21–27. [CrossRef]
18. Burbaum, U.; Sass, I. Physics of adhesion of soils to solid surfaces. *Bull. Eng. Geol. Environ.* **2017**, *76*, 1097–1105. [CrossRef]
19. Alshameri, B. Maximum dry density of sand–kaolin mixtures predicted by using fine content and specific gravity. *SN Appl. Sci.* **2020**, *2*, 1693. [CrossRef]
20. Li, H.; Zhang, Z.; Zhai, J.; Yang, L.; Long, H. Correlation between Soil Structural Parameters and Soil Adhesion Based on Water Film Theory. *Coatings* **2022**, *12*, 1743. [CrossRef]
21. Daghistani, F.; Baghbani, A.; Abuel Naga, H.; Faradonbeh, R.S. Internal Friction Angle of Cohesionless Binary Mixture Sand–Granular Rubber Using Experimental Study and Machine Learning. *Geosciences* **2023**, *13*, 197. [CrossRef]
22. Daghistani, F.; Baghbani, A.; Abuel Naga, H. Shear strength characteristics of binary mixture sand-carpet fibre using experimental study and machine learning. *Int. J. Geotech. Eng.* **2023**, 1–15. [CrossRef]
23. Li, C.; Kong, G.; Liu, H.; Abuel-Naga, H. Effect of temperature on behaviour of red clay–structure interface. *Can. Geotech. J.* **2019**, *56*, 126–134. [CrossRef]