Interfacial Shear Adhesion between Compacted Kaolin Clayey Soil and a Metallic Material

Submitted by

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List of Symbols

Symbol	Denotation	Unit
γ	Unit weight, Bulk unit weight, Moist unit	$kN\backslash m^3$
γ_d	Dry density	$g\backslash cm^3$
$\gamma_{d\ max}$	Maximum dry density	$g\backslash cm^3$
$\Delta\ \gamma_d$	Change in dry density	$g\backslash cm^3$
W	Total weight of soil	g
W_m	Weight of compaction mould	g
V	Volume of soil	cm^3
V_m	Volume of mould	cm^3
wc	Water content or moisture content	%
OMC	Optimum Moisture Content	%
LL	Liquid Limit of soil	%
PL	Plastic Limit of soil	%
CI	Consistency Index	%
S_u	Suction of soil	pF
L_{max}	Maximum compression load applied by	kN
Δ_{max}	Maximum displacement occurred during testing	mm
α	Interfacial adhesion of soil	kPa
$\Delta\alpha$	Change in adhesion of soil	kPa
$\Delta\ \gamma_d$	Adhesion slope	-
R	Rate of adhesion change per dry density change.	-
A	The internal surface area of mould	cm^2

Abstract

Soil has an ability to adhere to materials. Several problems in soil in terms of shear adhesion occurs at the interface of soil and materials (e.g. concrete, steel, timber) are encountered. Parameters that affect interfacial shear adhesion are soil properties, material roughness and the testing conditions.

In this study, a novel interfacial shear adhesion testing method is developed where its concept is based on simplicity of procedure and availability of equipment. It involves using the conventional compaction mould where the required force to extrude the compacted soil specimen is measured. This extrusion force applies shear on the interface between the compacted soil and the inner wall of the compaction mould. Consequently, the interface shear adhesion resistance between the compacted soil and the compaction mould can be determined. A constant displacement loading machine was used to extrude the compacted soil specimen from the compaction mould. Kaolin clay and a mixture of kaolin with sand are the testing soils in this study. The soils were compacted at different energy levels and moisture contents to investigate the effect of these variables on adhesion shear behaviour.

The test results show that soil adhesion is affected by soil composition, moisture content and dry density. The study reveals that the effect of moisture content on soil adhesion depends on the soil composition, and it changes as the sand content increases. As the sand content increases, the soil adhesion decreases. However, the results show that an increase in dry density leads to an increase in soil adhesion regardless of the soil composition. The adhesion of each soil type shows different stages as moisture content increases. The

evolution of these stages depends on the role of soil matric suction and density on the adhesion.

Statement of Authorship

Except where reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis accepted for the award of any other degree or diploma. No other person's work has been used without due acknowledgment in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

Rayed Almasoudi

02 June 2020

Acknowledgment

Firstly, I would like to thank Allah the Almighty for granting me the capability to complete this thesis. This thesis has been completed due to the assistance and guidance of great people who deserve sincere thanks and appreciation.

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In addition to the main supervisor, I would like to thank my co-supervisor Dr Hamayon Tokhi for his insightful comments and encouragement, and also for answering the technical question in the labs which has widened the research from various perspectives.

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Last but not least, I would like to thank my family for their support throughout this research journey.

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CHAPTER 1:

Introduction

1.1 Background

Soil is encountered in several fields such as agriculture and civil engineering. The phenomena of soil adhesion occur at the interface between soil and other materials which results in some issues. Soil adhesion is defined as the ability of soil to stick to other materials. The behaviour of soil adhesion varies according to soil properties, construction material type and roughness.

Pile foundations and retaining walls are subjected to an interfacial shear adhesion stress that could have some unexpected cost implications. Tunnelling projects must deal with soil adhesion as the soil could cling onto the cutter head of the tunnel boring machine (TBM). Agriculture faces severe issues related to soil stickiness in the field when soil becomes stuck to agricultural machines which cause a high consumption of energy and low efficiency. Hence, there is a great need to understand the engineering behaviour of soil adhesion to other materials.

1.2 Aim and Scope

This research aims to investigate the behaviour of adhesion at the interface of soil and the internal surface of a compaction mould. Ninety-four compacted soil specimens, which differ in terms of soil composition, moisture content and compaction energy, are tested in this study. The scope of this research are as follows:

1. Conducting an intensive literature review in the field of soil-construction material adhesion behaviour and identifying any gaps of knowledge in this field.
2. Developing a new and simple test method to measure the adhesion between soil and other materials.
3. Conducting experiments to assess the effect of the following factors on the adhesion between clayey compacted soil and a metallic solid surface:
    a) Sand content
    b) Moisture content
    c) Dry density
4. Analysing the experiment results to introduce robust interpretations of the observed compaction and shear adhesion test results.

1.3 Thesis Structure

This thesis consists of six chapters. A brief description of each chapter follows.

CHAPTER 1 introduces this research and includes background information and the aims and scope of this study.

CHAPTER 2 presents the principles, concepts and definition of soil adhesion. It also discusses the importance, applications and issues of soil adhesion in some fields. This chapter also includes a literature review of past studies and their limitations.

CHAPTER 3 explains in detail the newly developed shear test method for adhesion proposed in this study. It also describes the geotechnical properties of the soils used in this study.

CHAPTER 4 presents the results and findings from the experiments. It discusses the effects of sand content, moisture content, and dry density on the behaviour of soil shear adhesion and compaction.

CHAPTER 5 concludes the thesis and summarises the outcomes of the study. It also makes some recommendations for further studies.

CHAPTER 2:

Literature Review

2.1 Introduction

Understanding the process of binding materials together at interfaces is essential in various branches of technology, such as tribology, micro-electronics, and civil engineering, particularly, geotechnical engineering (Shukla 2014). In geotechnical engineering, soil particles adhere to other materials in the presence of water at their interface (Fountaine 1954). Different types of soils have different levels and behaviour of interfacial adhesion (Sony and Salokhe, 2006).

The interest in understanding soil stickiness dates back to the early 20th century (Atterberg 1911; Keen & Coutts 1928; Hardy 1928). This chapter presents a review of the literature in the area of soil adhesion. It includes the definition of soil adhesion and its applications in the engineering field, the available laboratory testing methods and their advantages and limitations, and factors to control soil adhesion behaviour.

2.2 Definition of Soil Adhesion and Cohesion

Adhesion describes the tendency of certain materials to cling to other materials (Basmenj et al. 2016). Adhesion is affected by the contact area, which is controlled by the normal load, the roughness of the surface area, and soil properties (Bhushan, 2003). Therefore, soil adhesion can be defined as the ability of a component of soil to stick to other surfaces. The adhesion is controlled by the properties of three elements: soil, solid surface and their interfaces (Jia, 2004). In other words, adhesion forces depend on soil composition and properties (water content, matric suction), solid surface properties (roughness, hardness) and the contact area and duration between soil and the solid surface (Soni and Salokhe, 2006).

Soil cohesion is different from soil adhesion. Cohesion, as a concept, is the act of similar materials sticking together. In soil mechanics, the cohesion is the force that bonds together water molecules in clayey soil (Alberto-Hernandez et al. 2017). It is important to understand the properties of soil, adhesion and cohesion in geotechnical design. However, this thesis only focuses on studying the behaviour of soil adhesion. Figure (2.1) illustrates the concepts of both the adhesion and cohesion of soil.

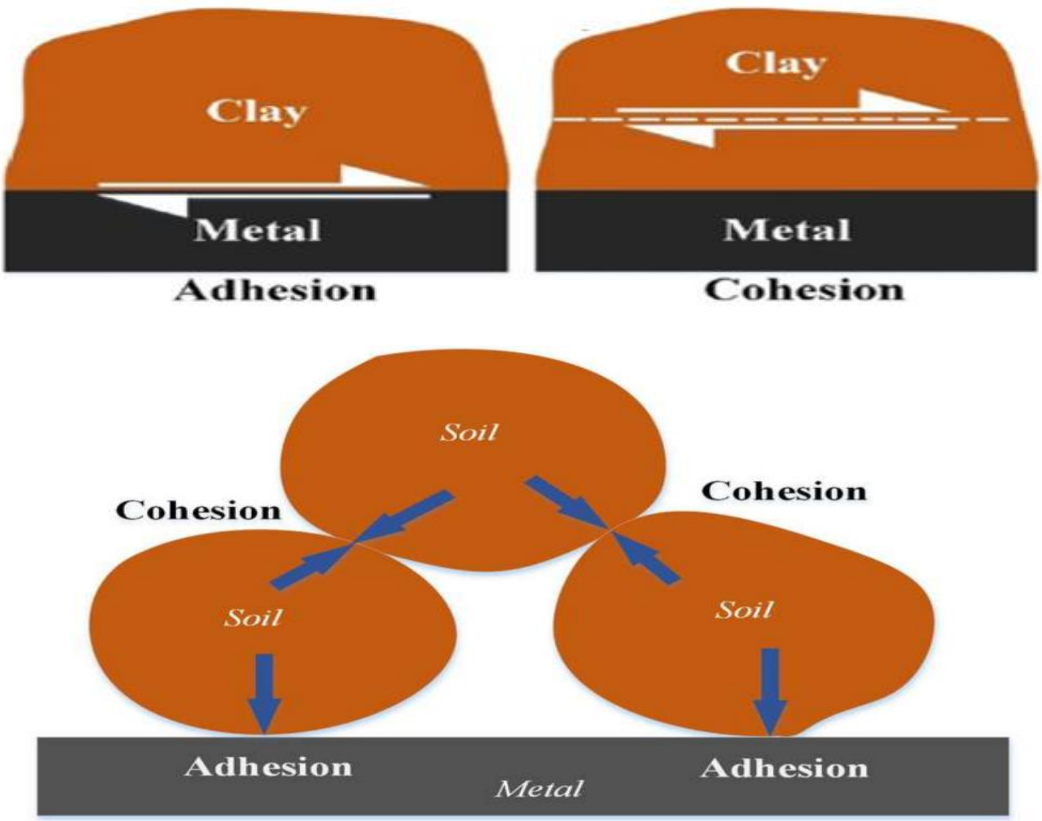

Figure 2.1 Illustration of adhesion and cohesion of soil (Alberto-Hernandez, Kang, Yi and Bayat, 2017).

According to Tong et al. (1994), there are two types of soil adhesion, normal adhesion and shear (tangential) adhesion. Each type of adhesion takes place according to the type of forces applied at the soil–continuum interface. If shear force is applied to this interface, shear adhesion occurs, whereas if normal tensile is applied, normal adhesion occurs. Fountaine (1954) assumes that the adhesion of soil to other materials occurs due to the existence of two mechanisms, water film at the interface (capillary adhesion) and the attraction of soil particles to the surface of other material (chemical adhesion).

2.3 Applications of Soil Adhesion

2.3.1 Agriculture

The phenomenon of soil sticking to agricultural tools is a widespread problem in the agriculture (Fig. 2.2). It occurs when interfacial adhesion is larger than soil cohesion (Feinendegen et al., 2014). This scenario causes difficulties in the process of tillage and harvesting and therefore affects the quality of crops (Fountaine, 1954). Also, it is an issue when wet soil becomes stuck in agricultural tools and affects their working efficiency, and therefore life span (Sass and Burbaum 2008). High energy consumption is a serious issue that results from the resistance of tillage tools against soil stickiness (Liu et al., 2019).

Figure 2.2 Soil sticking to agricultural equipment (Shropshire Star 2018).

2.3.2 Construction field

According to Sarsby and Meggyes (2001), an understanding of the behaviour of soil adhesion in relation to materials is important in designing many geotechnical structures. Soil-construction material interfacial adhesion takes place in many geotechnical works, such as retaining walls (Keshavarz and Ebrahimi, 2016), anchor rods, piles (Sladen, 1992), soil reinforcement, etc. (Figs. 2.3, 2.4, and 2.5, respectively). This interfacial adhesion, if not taken into consideration, might lead to an overly conservative design (Goshtasb et al. 2020). For instance, in Canada, conservative designs have been adopted for heavy infrastructure projects, such as concrete piles and deep retaining walls which results in overly foundation expensive designs. This could have been prevented and costs would have been reduced if adhesion had been taken into consideration (Taha and Fall, 2013). Adhesion also plays a major role in controlling the bit balling problem which occurs during the process of drilling in clayey soil and causes a decrease in the rate of penetration (Wells et al. 2008; Ma et al. 2012).

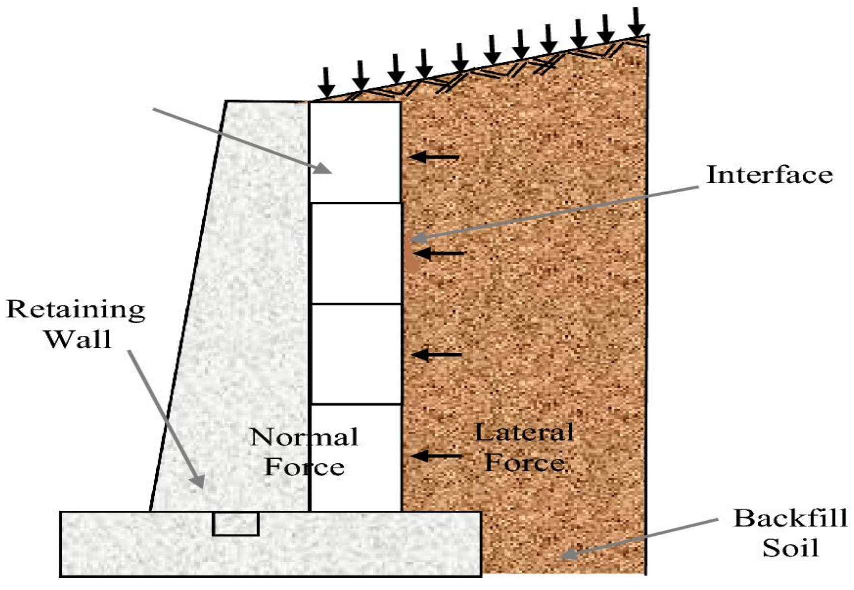

Figure 2.3 Soil adhesion at the interface of retaining walls (Meguid and Khan, 2019).

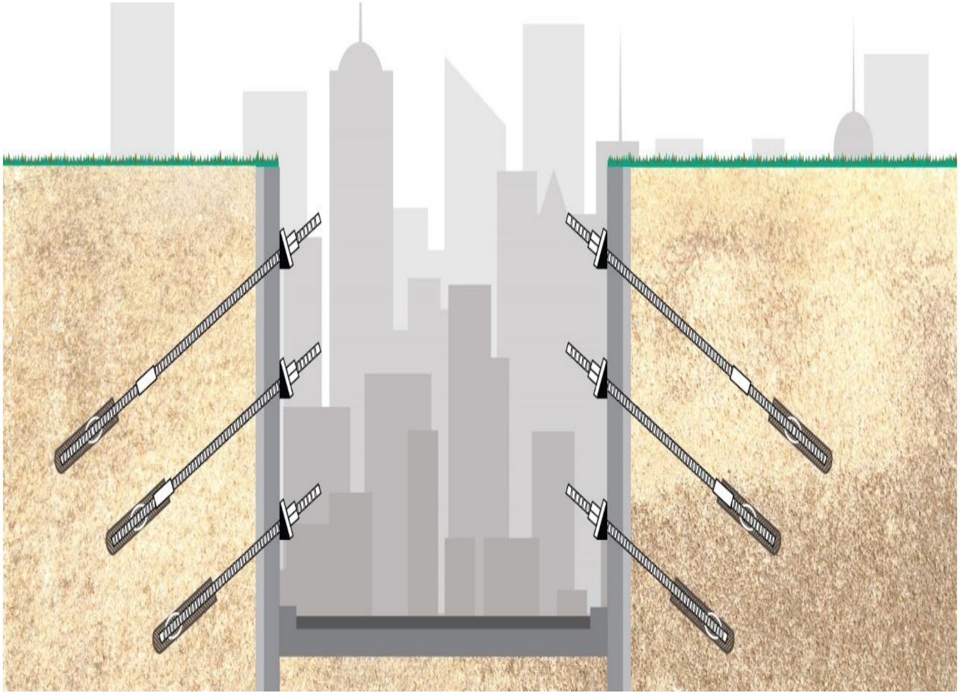

Figure 2.4 Soil adhesion at the interface of anchor rods (Dextra, 2018).

Figure 2.5 Soil adhesion at the interface of piles (http://geosolv.ca/helical-piles/helical-piles-2/).

2.3.3 Tunnelling field

In the field of transportation and tunnelling, tunnel boring machines (TBMs) have been used extensively for tunnelling construction (Fig. 2.6). Many studies have been carried out on the clogging or sickness of clay which causes it to adhere to the cutter head of tunnelling machines (Atkinson et al. 2003; Jancsecz et al. 1999; Schlick 1989). The TBM machine faces potential clogging issues during boring in cohesive soil due to soil-metal interfacial adhesion (Alberto-Hernandez et al., 2017). The level of clogging risk varies depending on the consistency and plasticity of clayey soil (Thewes, 1999; Schlick 1989). This problem occurs when soil is stuck in the cutter edge or other parts of the equipment (Ye et al. 2017; Liu et al. 2018; Hollmann and Thewes 2013). This results in difficulties in work, progress delay and high cost (Hollmann et al., 2005). Hence, investigating the behaviour of soil adhesion on solid surfaces is crucial to predict the potential risks that could occur and to find a method to reduce soil adhesion if required.

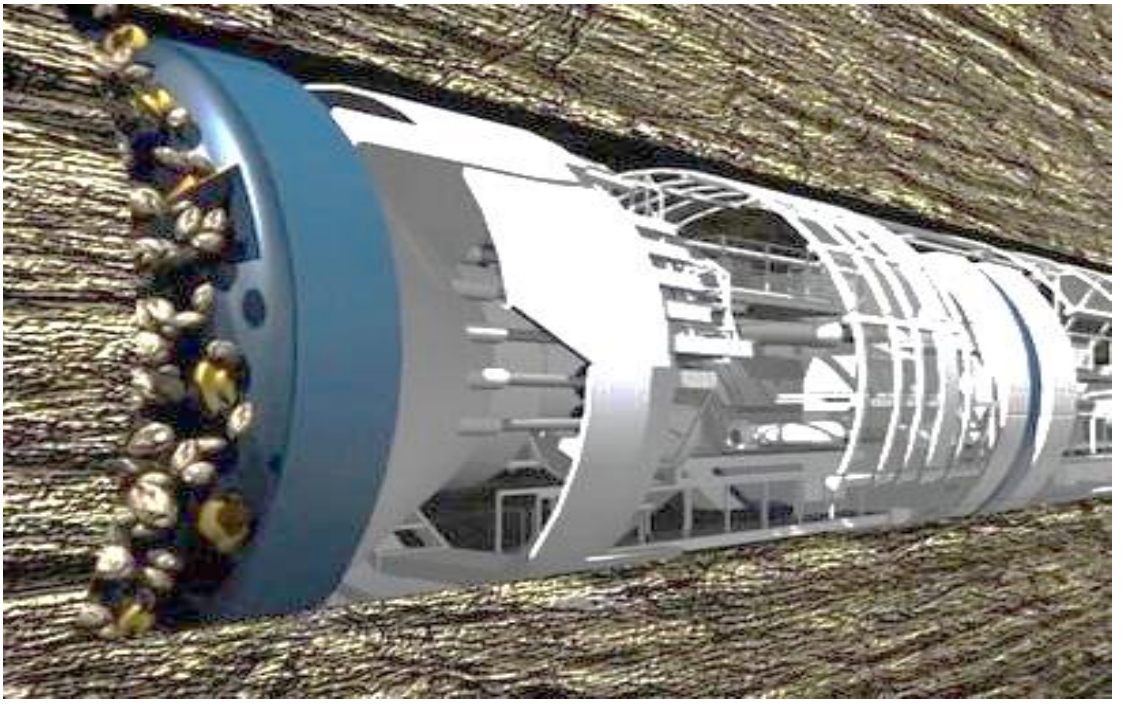

Figure 2.6 Interfacial soil adhesion during tunnelling (openPR.com, 2019).

2.4 Methods of measuring interfacial soil adhesion

Soil adhesion can be measured by several methods, which can be classed as either direct or indirect. The direct technique of adhesion measurement involves carrying out lab experiments such as the pull-out (Thewes and Burger, 2005), piston separation (Basmenj et al., 2016) and shear plate tests (Zumsteg and Puzrin, 2012). Tangential adhesion is measured by the modified direct shear test (Basmenj et al., 2016). However, there is no standard method or device for soil adhesion measurement (Alberto-Hernandez, et al., 2017). Few studies have been directed to assess the interfacial adhesion between soil and construction materials.

Fountaine (1954) studied soil adhesion in relation to different materials under a controlled moisture tension condition. He conducted six experiments using six different types of materials using loam clay and sandy clay. The tests were conducted under the effect of both constant and rapid loading. The water content of soil was constant in these experiments with an addition of some dispersion liquids into the water to investigate the effect of water surface tension on soil adhesion. Fountaine (1954) used a special adhesion test apparatus (Fig. 2.7) to measure normal soil adhesion. The soil specimens were placed in a plate of 5cm diameter and 1cm thickness. A known load is applied to the soil specimen for a given time and a water line running through the nozzle was used to control water tension. Once the soil-material adhesion was damaged, the plate pulled out of the soil. Fountaine (1954) found that adhesion is affected by the water content of the soil and the type of materials. He also found that soil containing sand has lower adhesion than clay.

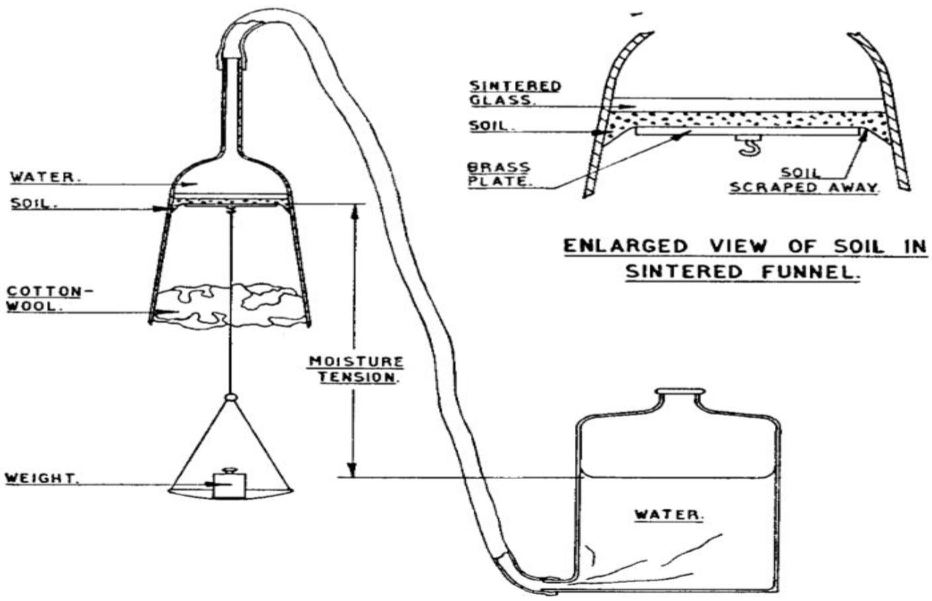

Figure 2.7 Plate apparatus to measure adhesion used by Fountaine (1954).

Thewes and Burger (2005) studied the behaviour of normal soil adhesion to steel in their investigation into the clogging issue of TBMs. They used the piston pull-out method (Fig. 2.8) in which a steel piston is vertically pulled out from the soil to measure adhesion. The effect of several parameters on adhesion such as soil consistency, contact time between soil and piston and wetting fluid types was evaluated. It was found that normal adhesion depends on clay minerals and soil consistency. They found that normal adhesion increases with an increase in soil consistency which depends on water content.

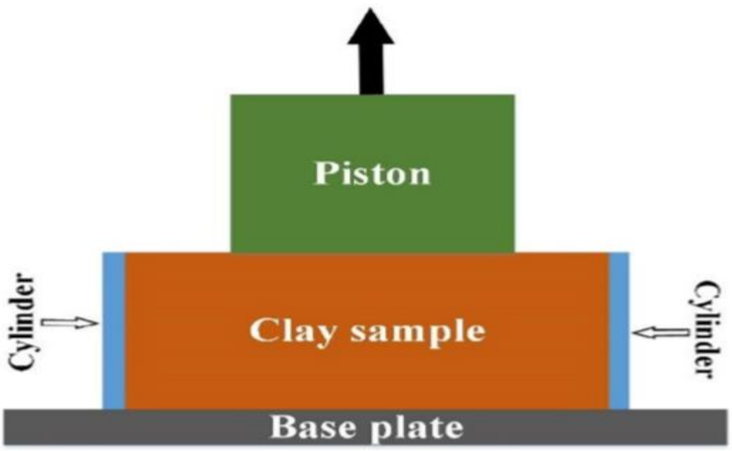

Figure 2.8 Piston pull-out method used by Thewes and Burger (2005).

Azadegan & Massah (2012) studied the effect of temperature on the adhesion of clay to steel. They used clay of a 50 ~ 80 % degree of saturation and used a refrigerator and oven to control the temperature. A specific instrument that has a pulley was designed to measure normal adhesion, as shown in Fig. 2.9. A metal plate was placed on top of the soil specimen and water was allowed to drop steadily into the container until the soil sample detached from the plate and then the amount of water in the container was measured. This procedure was repeated at different temperatures, after which adhesion was calculated as the difference between the weights of the water added and the plate. They found that adhesion decreases as the temperature increases.

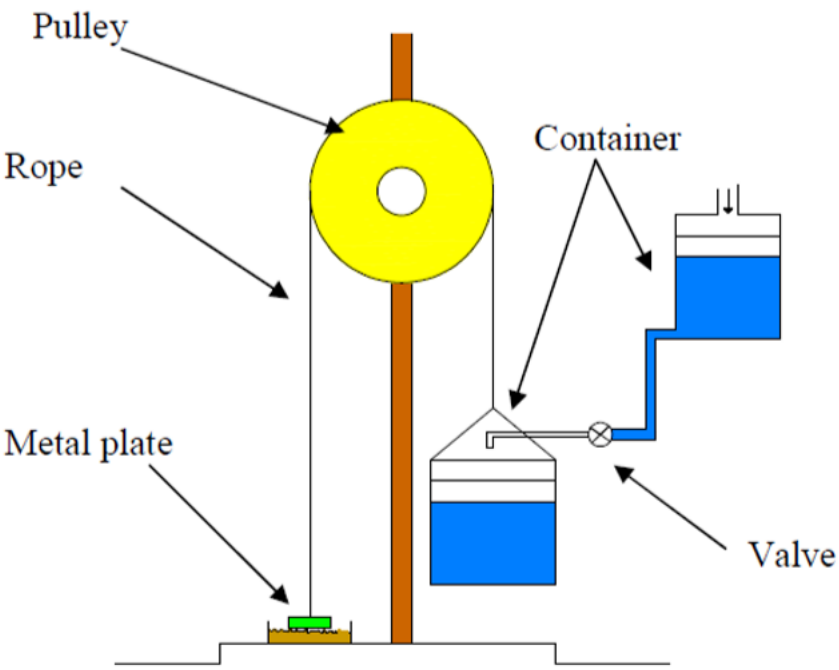

Figure 2.9 Normal adhesion apparatus used by Azadegan & Massah (2012).

Basmenj et al. (2016) conducted a study to measure the normal adhesion of soil to metal. They used a piston separation device to measure normal adhesion, as shown in Fig. 2.10. The tests were conducted on compositions of clay and sand at different levels of wetness. The clay used was more montmorillonite but less kaolinite. The pull-out method was used where the soil mould was fixed at a movable base, and the piston was fixed on top of the device. The soil mould was moved upward to reach the fixed steel piston. Then, the movable base was reversed after a known time to allow the soil to detach from the steel piston, and the separation rate was determined. Adhesion was calculated by dividing the applied load by the contact area of the piston. Their study revealed that normal adhesion is clearly related to soil wetness.

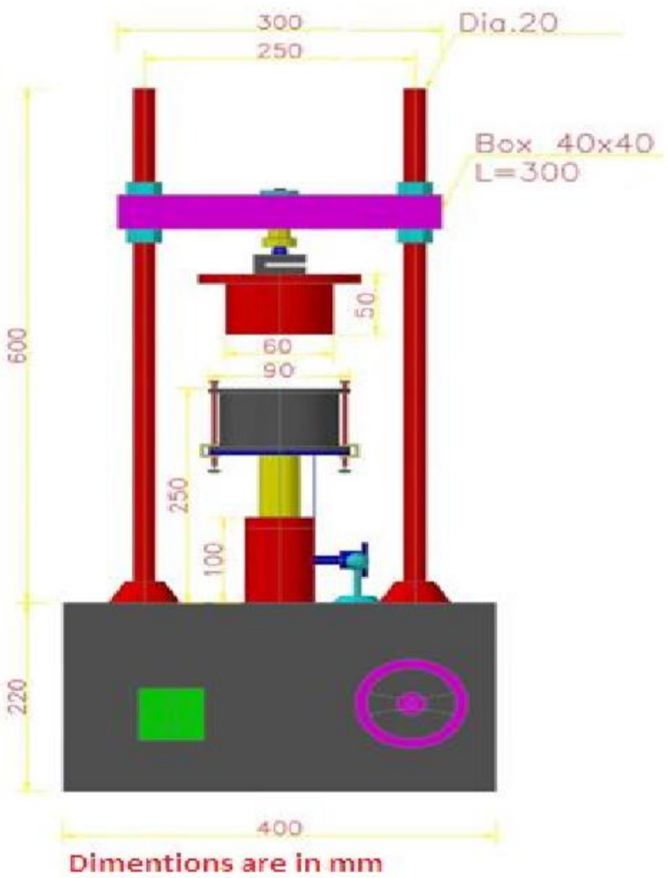

Figure 2.10 The piston separation device used by Basmenj et al. (2016).

Burbaum and Sass (2017) studied the behaviour of normal soil adhesion to steel surfaces. They used the pull-out load test in which soil separation from the steel surface occurs. Clay was used in their study, and the soil samples were prepared by standard Proctor compaction. The adhesion test apparatus is shown in Fig. 2.11. The soil samples were placed in the sample ring at different water contents. The cylinder of the adhesion device applied a vertical constant compression load on the soil and then was released to allow soil separation to occur. Burbaum and Sass (2017) also investigated the effect of consistency and water content on clay adhesion and found that adhesion is dramatically influenced by the soil consistency index. The test results showed that low adhesion of clay could occur when the wetness of the solid surface is low.

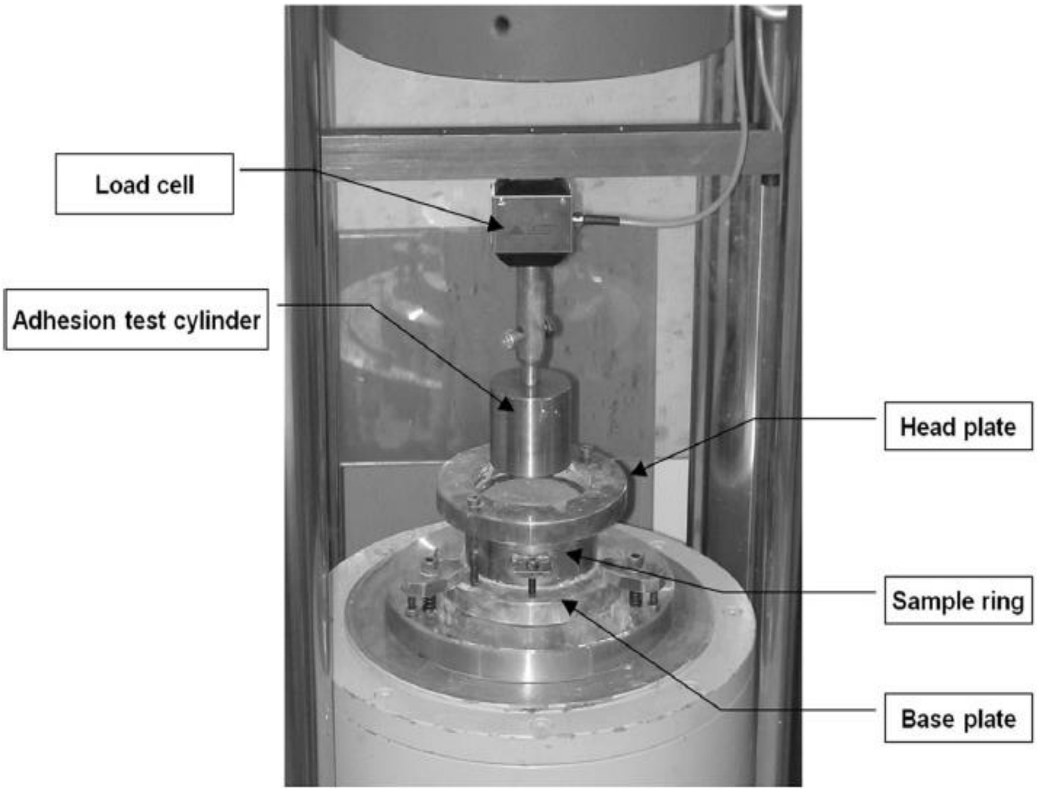

Figure 2.11 Adhesion test apparatus used by Burbaum and Sass (2017).

Zumsteg and Puzrin (2012) investigated the clogging issue that occurs in clayey soil during tunnelling. Clogging occurs due to soil stickiness which was found to be correlated to tangential adhesion. A plate apparatus that consists of a soil box and rotating metallic rod was used to measure the maximum torque during the test, as shown in Figs. 2.12 and 2.13. Tangential adhesion (a) was calculated as follows:

$$a = \frac{6\, T_{max}}{\pi D^3} \quad (1)$$

where T_{max} is the peak torque and D is the diameter of the rotating plate. The soil mixtures used in their tests were kaolin, illite and bentonite. They claimed that the plate device they used provides more precise results in relation to tangential adhesion measurement. Tangential adhesion was found to be an influencing factor affecting the stickiness of soil.

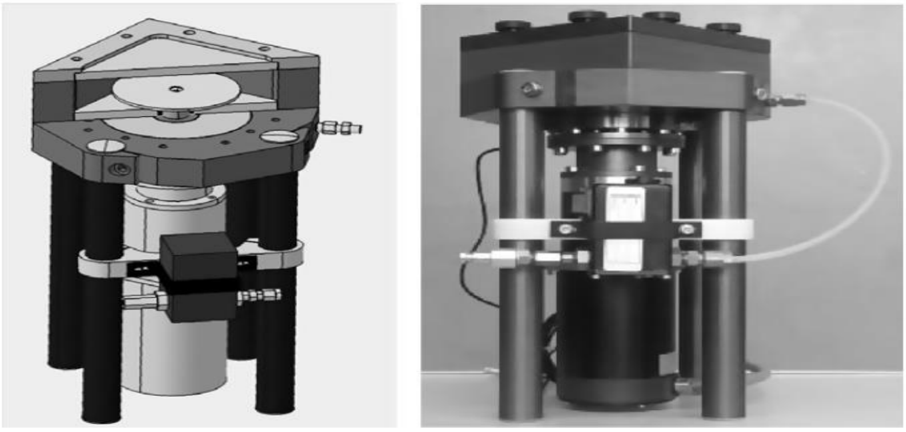

Figure 2.12 The plate apparatus used by Zumsteg and Puzrin (2012).

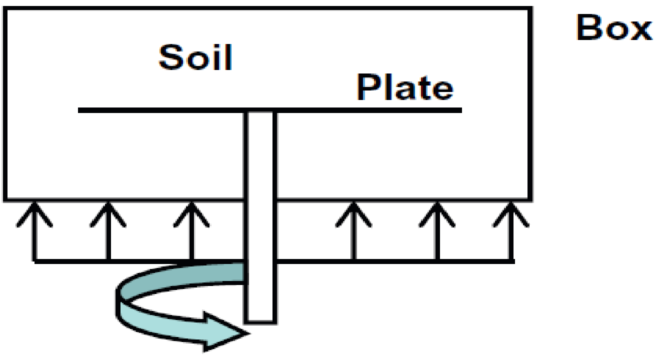

Figure 2.13 Concept of the plate apparatus used by Zumsteg and Puzrin (2012).

Table 2.1 briefly summarises the past studies that have been carried out by many researchers in the field of soil adhesion.

Table 2.1 Literature summary of soil adhesion measurement.

Author	**Literature**
FOUNTAINE (1954)	*Aim*: To study the effect of materials on soil adhesion at fixed moisture tensions.
	Material: Soil to different materials.
	Device: Special adhesion apparatus.
	Findings: Soil adhesion is affected by the water content of soil and the type of materials.
Thewes & Burger (2005)	*Aim*: To evaluate the adhesion.
	Material: Soil to Steel.
	Device: Piston pull-out.
	Findings: Normal adhesion depends on the clay minerals and the consistency of the soil.
Azadegan & Massah (2012)	*Aim*: To study the effect of temperature on adhesion.
	Material: Clay to steel.
	Device: Specific designed instrument.
	Findings: Adhesion decreases as temperature increases.
Zumsteg & Puzrin (2012)	*Aim*: To assist the soil stickiness and its correlation to adhesion.
	Material: Clay to steel.
	Device: Plate apparatus.
	Findings: Stickiness correlates to tangential adhesion.
Basmenj et al. (2016).	*Aim*: To measure normal adhesion.
	Material: Soil to metal.
	Device: The piston separation device.
	Findings: Adhesion is related to soil wetness.
Burbaum, U. & Sass, I. (2017)	*Aim*: To measure normal adhesion.
	Material: Adhesive soil to solid surfaces.
	Device: Adhesion test apparatus.
	Findings: Adhesion of soil to solids depends on the water film at the interface.

2.5 Factors affecting interfacial soil adhesion

Several factors affect the value of soil adhesion on other materials, as listed in Fig. 2.14. However, not all factors have been investigated (Alberto-Hernandez, et al., 2017). These factors can be classified into three categories: soil parameters, material parameters and testing condition parameters. The soil properties play an essential role in soil-solid adhesion. These soil properties include soil type (grain size distribution, mineralogy), porosity, specific surface area (SSA), moisture content, water salinity, plasticity, consistency and cohesion (Jia, 2004; Sass and Burbaum, 2008). The continuum material parameters include material types and surface roughness (Sass and Burbaum, 2008), whereas the testing condition parameters involve contact time at the soil interface, loading rate, humidity and temperature of the interface surface (Satomi et al., 2012; Sass and Burbaum, 2008).

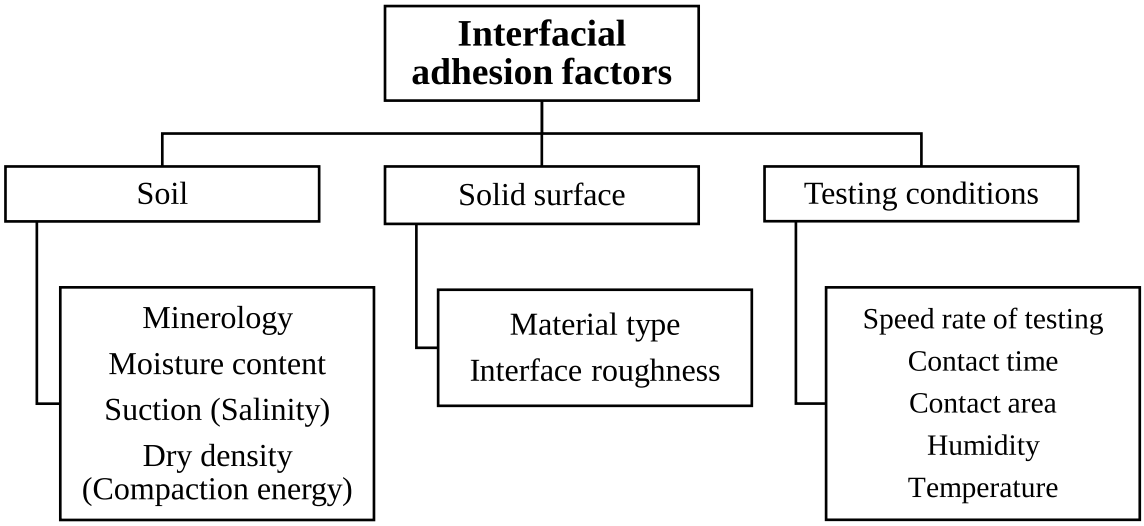

Figure 2.14 Factors affecting interfacial soil adhesion.

2.5.1 Soil Type

Soil composition is a vital factor that affects soil adhesion (Alberto-Hernandez et al., 2017). Different soils show different amounts of adhesion based on their mineral content. According to Littleton (1976), clay soils have strong adhesion to certain material surfaces such as concrete. Clayey soils demonstrate stronger adhesion than sand due to their wettability behaviour. Even different types of clay have different adhesion due to the diversity in their inherent properties such as clay minerals, specific surface area (SSA) and cation exchange capacity (CEC). For example, the adhesion of montmorillonite is much larger than kaolinite (Donahue and Shickluna, 1977). The small size of clay particles, as shown in (Fig. 2.15), assists in filling the small pores at the interface surface, which causes a larger interface contact surface area between soil and materials and therefore leads to stronger adhesion (Basmenj et al., 2016). Also, the increase in the CEC of the clay causes an increase in plasticity, which then leads to an increase in adhesion (Kooistra et al., 1998). In general, as the clay content of the soil increases, adhesion increases accordingly (Chancellor, 1994).

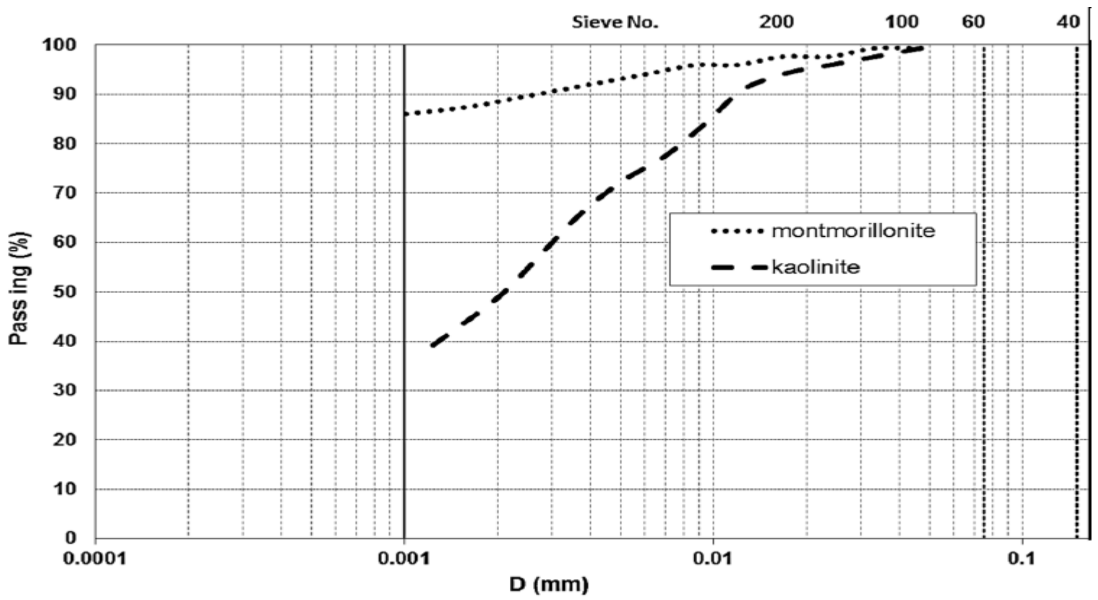

Figure 2.15 Particle size distribution chart shows the small size of clay particles (Basmenj et al. 2016).

2.5.2 Moisture Content, Consistency and Salinity

The moisture content of soil influences its ability to bond with other materials. Jancsecz (1991) stated that soil adhesion fluctuates as moisture content changes. Basmenj et al. (2016) reported that the adhesion of kaolin increases as moisture content increases, as shown in Fig. 2.16. However, the adhesion of montmorillonite increases up to certain water content then decreases beyond this water content limit, as shown in Fig. 2.17. Ren et al. (2001) found that soil adhesion is highest when the moisture content falls between the plastic limit and liquid limit. However, Yusu et al. (1990) stated that maximum adhesion occurs at the plastic limit. An excess of soil liquidity beyond the plastic limit decreases soil adhesion (Thewes, 1999; Burbaum, 2009; Weh et al., 2009; Feinendegen et al., 2011). The plasticity and the consistency of soil are interrelated and are significantly impacted by a change in the water content. Therefore, the soil adhesion value changes according to the value of the soil consistency which also depends on the clay minerals (Hollmann and Thewes, 2013; Basmenj et al., 2016). As moisture content decreases, the consistency index increases and soil adhesion decreases for the non-wetted clay surface condition, whereas it displays contrasting behaviour for the wetted clay surface condition, as shown in Fig. 2.18 (Burbaum and Sass, 2017). The wetted and non-wetted soil surfaces indicate the amount of water on the top of the soil surface.

Geodata (1995) and Thewes (1999) also studied the effect of the soil consistency index (I_c) on the adhesion of clay.

$$I_c = \frac{LL-w}{LL-PL} \qquad (2)$$

where w is the existing water content, and LL and PL are the liquid and plastic limits, respectively. Figure 2.19 shows the relationship between tangential adhesion and the consistency index at the interface of soil and steel. The tested soils were subjected to different levels of normal pressure before the adhesion test was conducted to assess the effect of the soil void ratio on adhesion behaviour. In general, the test results show that, regardless of the applied normal stress level, tangential adhesion increases as the consistency index increases and reaches its peak value close to the plastic limit (Liu et al., 2019). Furthermore, the test results also indicate that soil adhesion increases as the void ratio (normal pressure) of the soil increases.

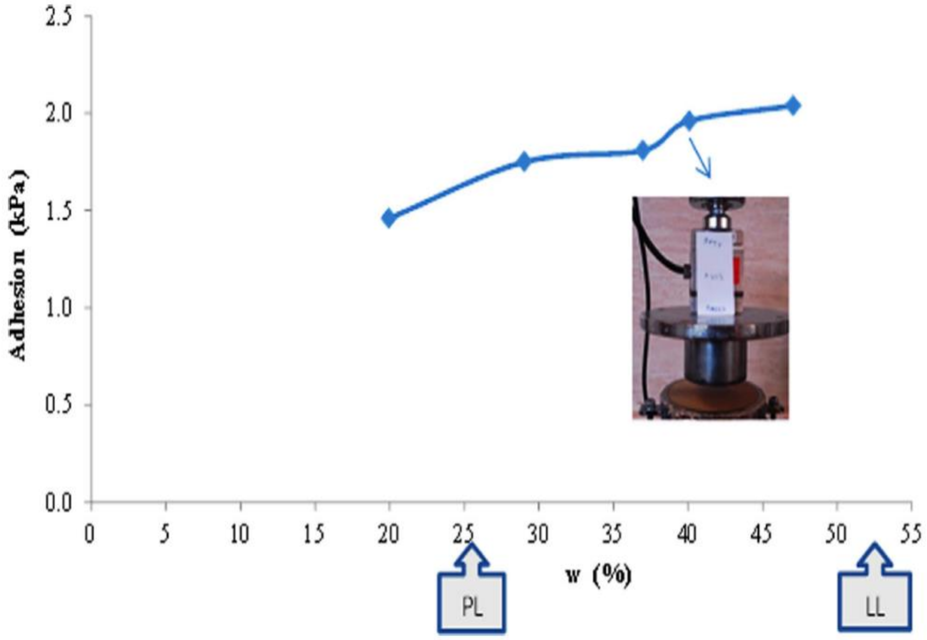

Figure 2.16 Montmorillonite adhesion behaviour against wetness (Basmenj et al., 2016).

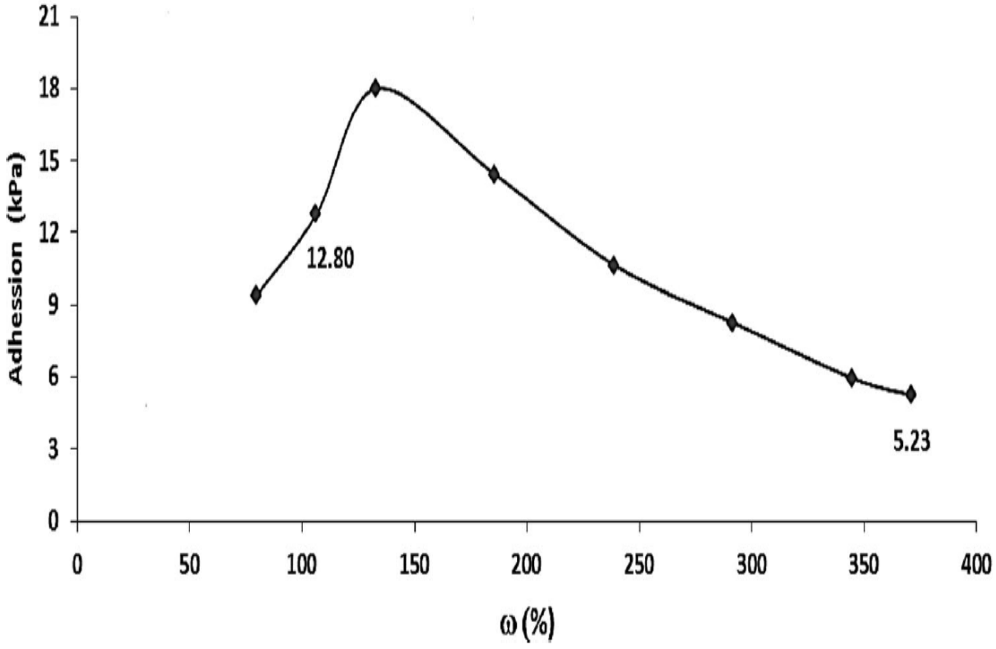

Figure 2.17 Kaolinite adhesion behaviour against wetness (Basmenj et al., 2016).

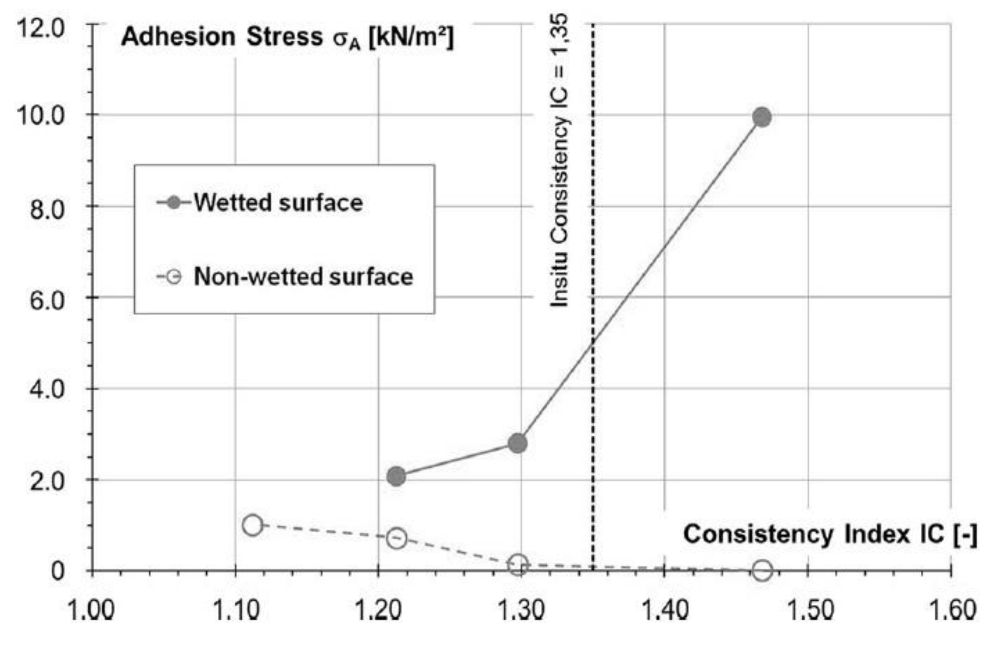

Figure 2.18 Adhesion vs consistency under the wetting conditions (Burbaum and Sass.2017).

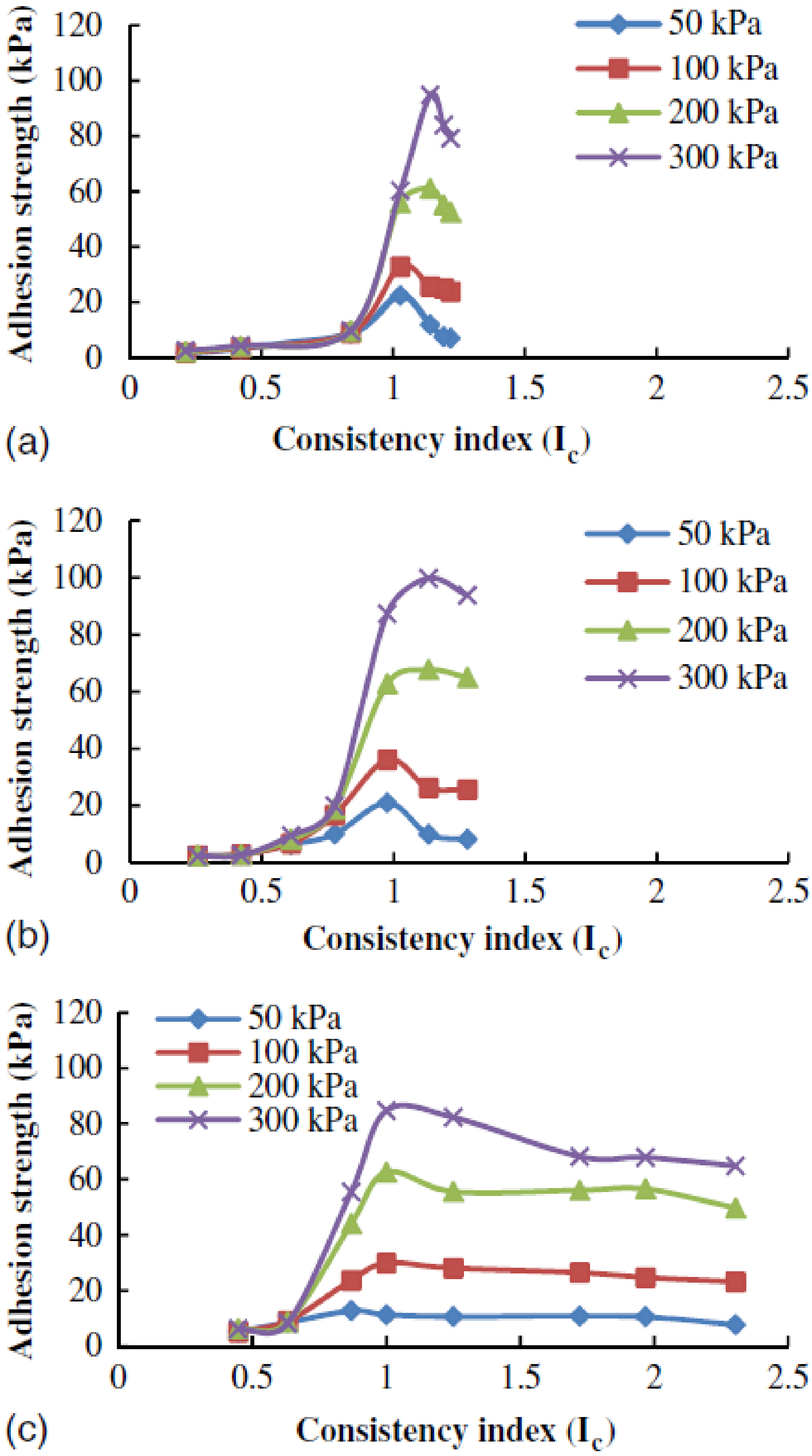

Figure 2.19 The effect of consistency indexes on tangential adhesion at different normal pressures; a) bentonite, b) mixture & c) kaolin (Liu et al. 2019).

To the best of the author's knowledge, none of the existing studies has focused on investigating the effect of water salinity on soil adhesion. However, Looker et al. (1939) used soluble salts to stabilise road surfaces and noted that the addition of salt increases the cohesion of clay. Adhesion occurs typically at the interface when it is larger than the soil cohesion itself (Feinendegen et al., 2011). Van Paassen and Gareau (2004) reported that as the salinity of the water content increases, the compressibility of clay increases accordingly. The rise of soil compressibility means an increase in dry density and a decrease in the permeability of clay (Kawai et al., 2016). Consequently, an increase in soil adhesion might be expected as increasing dry density leads to a higher interface contact area. More research is required to assess the effect of water salinity on the adhesion behaviour of clayey soil.

2.5.3 Dry Density

Jia (2004) stated that soil adhesion is related to soil properties. An increase in dry density at the dry side packs the soil particles closer, which decreases the soil voids and increases the SSA and the contact area of the soil interface (Bodman and Constantin, 1965). Thus, this concept could lead to an expectation of an increase in soil adhesion with an increase in dry density. The impact of dry density on soil adhesion can also be affected by certain soil properties such as moisture content, soil texture, and others (Ren et al., 2001). Burbaum and Sass (2017) stated that soil adhesion is influenced by the water saturation level, which is affected by dry density and the moisture content of the soil. Fig. 2.20 shows the relationship between soil adhesion and permeability as the consistency index (Ic) increases. The results indicate that both soil adhesion and permeability significantly increase as the moisture content increases beyond a certain Ic limit (CI=0.95). Therefore, soil permeability and adhesion could be related.

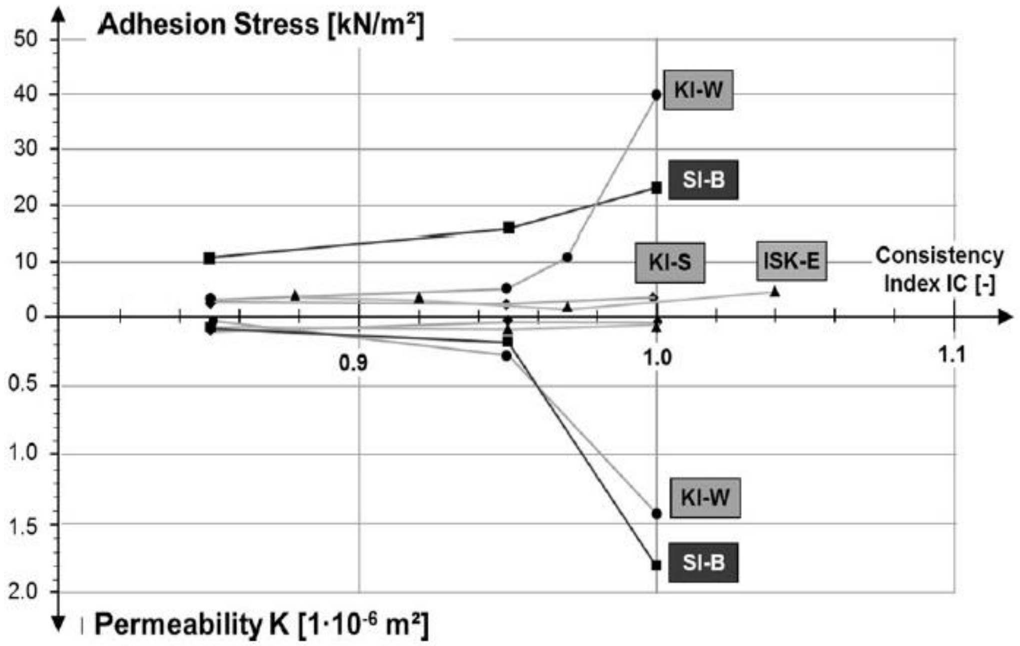

Figure 2.20 Correlation between adhesion, permeability and consistency (Burbaum and Sass 2017).

2.5.4 Normal pressure and contact area

Liu et al. (2019) stated that the tangential adhesion of kaolin, bentonite and a mixture of each behaves similarly under the effect of normal pressure. Tangential adhesion increases as normal pressure increases at a low moisture content. This linear relationship of tangential adhesion becomes curvilinear at Ic≈ 1.0 and high moisture content (W>PL), as shown in Fig. 2.21. Zumsteg and Puzrin (2012) recorded similar results for illite soil. They described the tangential adhesion of clay in terms of sliding resistance and showed its relationship with normal pressure applied to different types of soils, as shown in Fig. 2.22. Normal pressure affects soil adhesion as it has a direct relation with the contact area between the soil and steel. As normal pressure increases, the contact area of soil increases due to the plastic deformation. This linear relationship between normal pressure and the contact area of soil leads to an increase in soil adhesion. Basmenj et al. (2016) found that in the adhesion separation test, kaolinite separated from the steel surface faster than montmorillonite, the reason being that montmorillonite has smaller soil particles which leads to a larger contact area which, in turn, increases adhesion and delays the separation process, as shown in Fig. 2.23, (Kooistra et al., 1998).

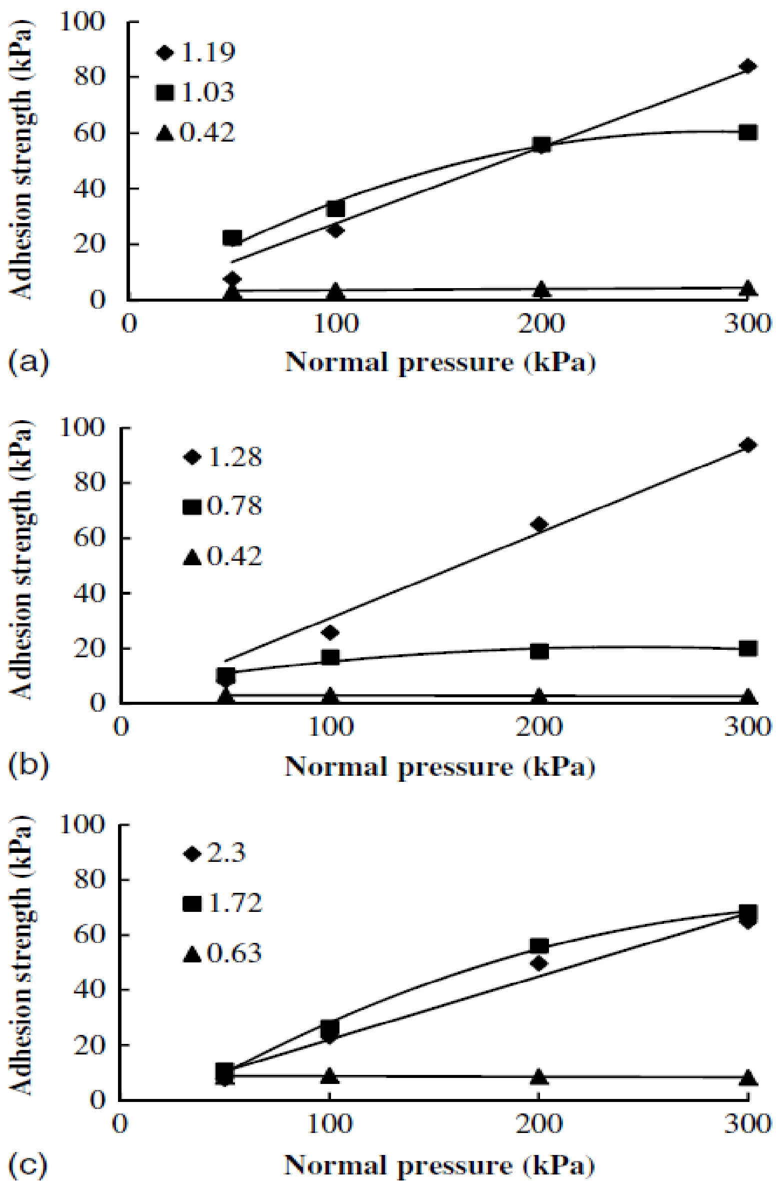

Figure 2.21 The effect of normal pressure on tangential adhesion at different consistency indexes; a) bentonite, b) mixture & c) kaolin (Liu et al., 2019).

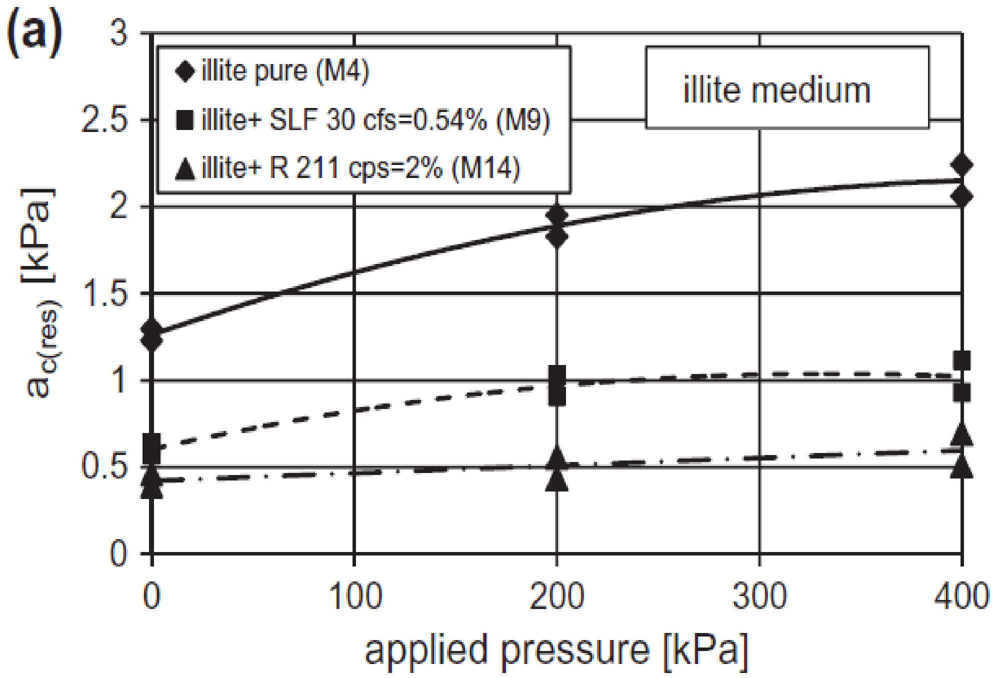

Figure 2.22 Sliding resistance against applied pressures for different clay mixtures (Zumsteg and Puzrin, 2012).

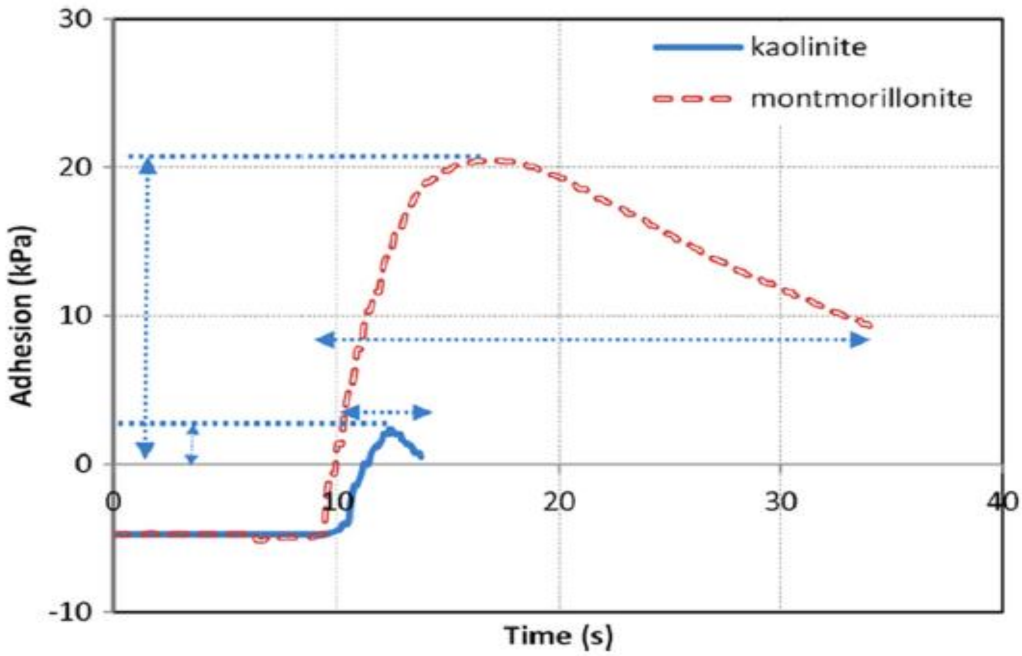

Figure 2.23 The separation times vs adhesion for kaolinite and montmorillonite (Basmenj et al., 2016).

2.6 Conclusion

Soil adhesion is the ability of soil particles to adhere to other materials. The value of soil adhesion relies on several parameters; some are related to the soil, such as soil mineralogy, particle size, dry density, porosity, moisture content, the salinity of water content, consistency, suction, etc. Others are related to materials such as material type, the surface roughness and contact area. Also, the testing environment plays a role in influencing adhesion. This includes loading rate, contact duration, room temperature and humidity. There are two types of soil adhesion which are based on the type of applied load, namely shear adhesion and normal adhesion. The importance of investigating soil adhesion is the understanding it gives in relation to potential issues that occur in several fields. Soil clogging and stickiness are common problems in relation to agricultural works, construction projects and tunnelling. Several researchers have investigated the adhesion of soil to other materials using different methods and devices.

The previous studies were carried out on clay and sand-clay mixtures to investigate soil adhesion to materials such as steel and rubber. The rotating plate, pull-out and soil separation tests were used to measure soil adhesion. The studies revealed important factors that affect soil adhesion. Soil composition and particle size play a role in the adhesion value where clay has a larger adhesion than other less adhesive soils. Kaolin has a larger particle size than montmorillonite which means a smaller specific surface area and less adhesion. Moisture content has a significant influence on soil adhesion and determines the maximum value of adhesion at the plastic limit. The adhesion of clay mostly increases under the effect of applied pressure. Soil adhesion typically increases as dry density increases. However, the effect of soil water salinity on its adhesion behaviour has not yet been assessed.

CHAPTER 3:
Experimental Method and Program

3.1 Introduction

This study investigates the interfacial adhesion of kaolin clay under different conditions. This chapter presents the materials and the testing method used in this study. It also describes in detail the laboratory testing procedures and the equipment used for this purpose which are simple to be conducted in the geotechnical lab without any complications. The repeatability of the test results using the testing method proposed in this study is also discussed in this chapter.

3.2 Materials

The experiments were carried out on two types of soil composition, pure kaolin clay and kaolin-sand mixture. This mixture includes two different percentages of sand that have been added to the kaolin to provide different soil composition. Sand percentages of 20% and 40% by weight are chosen in this study. Table 3.1 shows the mineral composition of kaolin. Tap water was used to compact the soil in the experiments.

Table 3.1 Mineral composition of kaolin.

Mineral	Mass percentage
Kaolinite	83.7
Muscovite	14.0
Quartz	2.3

The geotechnical properties of kaolin used in this study are listed in Table 3.2. Figure 3.1 shows the particle size distribution of kaolin and silica sand used in this study. The specific gravity and the minimum and maximum void ratios of the sand used in this study are 2.65, 0.58, 0.97, respectively.

Table 3.2 Properties of soil.

Properties	Kaolin
Liquid limit (%)	74
Plastic limit (%)	32
Plasticity Index	42
Gs	2.58
Cation exchange capacity (meq/100g)	0.075
Total surface area (m2/g)	20
Surface charge density (µC/m2)	0.36
Main chemical composition (weight %)	
SiO_2	45.2
Al_2O_3	38.8

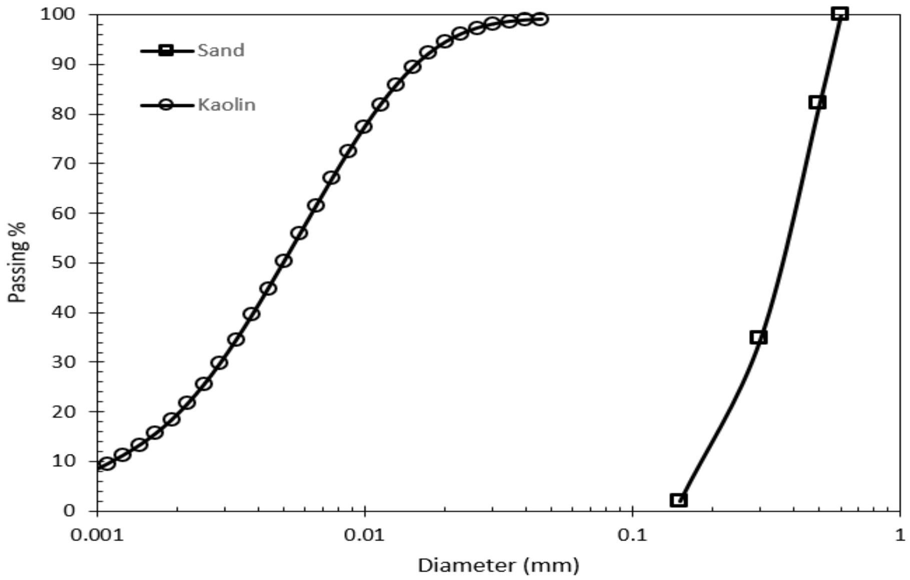

Figure 3.1 Particle size distributions of kaolin and sand.

3.3 Shear adhesion test apparatus

The modified Proctor compaction mould is used in this study, as shown in Fig. 3.2. The internal dimensions of the mould are 152.4 mm in diameter and 132.4 mm in height with a volume of 2.42x10^{6} mm^{3}. The compaction mould includes a square base plate at the bottom, and a collar at the top and its total weight is 8.2 kg. A plastic circular plate of a thickness of 4 mm, as shown in Fig. 3.3, was added at the base of the compaction mould to facilitate the extrusion of the compacted specimen from the compaction mould in order to conduct the interface shear adhesion test. This plastic plate makes the net internal height of the mould equal to 128.4mm. Hence, the contact surface area between the compacted soil and the internal surface of the compaction mould is equal to 61475.2 mm^{2}.

An auto-compaction machine, as shown in Fig. 3.4, is used for soil compaction as it provides a better uniform distribution of the compaction energy over the soil specimen. A displacement-controlled LLOYD loading machine, as shown in Fig. 3.5, is used to extrude the compacted soil specimen. The extrusion process creates interface shear between the compacted soil and the inner wall of the compaction mould.

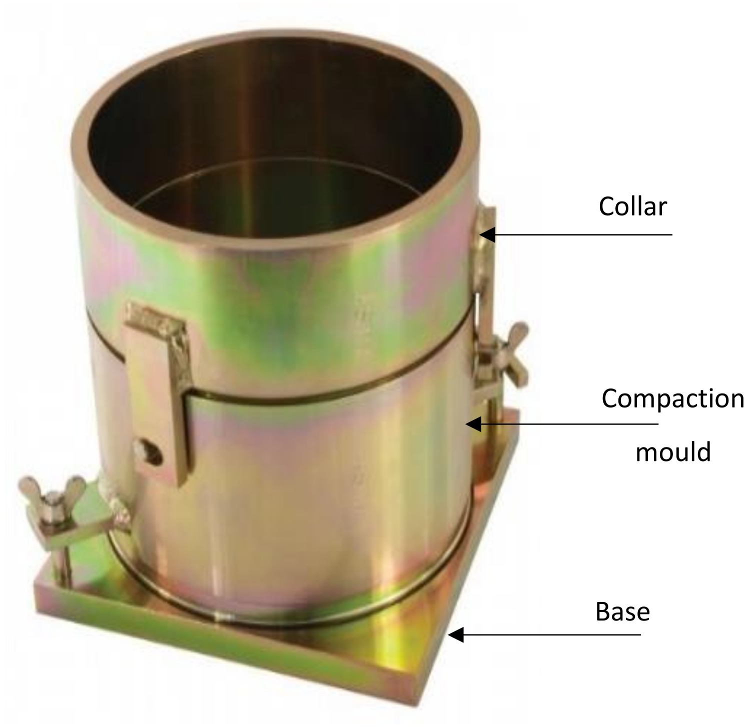

Figure 3.2 Compaction mould.

Figure 3.3 Plastic cover used during the soil adhesion test.

Figure 3.4 Auto-compactor machine.

Figure 3.5 LLOYD materials testing machine.

3.4 Sample preparation and experimental program

The experiments were carried out on soil specimens with moisture content ranging from 10% to 50%. Plastic sealed bags were used to store the moisturized soil after adding and mixing the various amounts of water. The moisturized soil remained in the sealed bags overnight for moisture equalization. Small specimens of soil were taken from these sealed bags to check the water content before compacting it in the compaction mould. The soil was compacted in the mould in three equal layers; each layer has the same amount of applied energy where every layer is almost 44 mm in thickness. The soil was compacted by different compaction energy levels (no. of blows) at the targeted moisture content to assess the effect of dry density on interfacial shear adhesion. A total of 90 tests were conducted, as listed in Table (3.3).

Table 3.3 Experimental program.

Soil type	Targeted wc (%)	No. of blows	Targeted wc (%)	No. of blows	Targeted wc (%)	No. of blows	Targeted wc (%)	No. of blows	Targeted wc (%)	No. of blows	Targeted wc (%)	No. of blows
100% K	10	15	20	15	25	15	30	15	40	15	50	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
80% K + 20% S	10	15	20	15	25	15	30	15	40	15	50	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
60% K + 40% S	5	15	10	15	15	15	20	15	25	15	30	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

3.5 Soil Adhesion Measurement

After compacting the soil in the compaction mould, the soil is ready for interface shear testing in the loading machine, as shown in Fig. 3.6. The compaction mould is fitted with the collar and placed upside down. Then, the metallic base of the compaction mould is removed to allow the compacted soil specimen to be pushed from the bottom side and extruded from the upside of the compaction mould. The compaction mould collar provides the required space for the extrusion process, as shown in Fig. 3.6. The loading machine applies a displacement-controlled load to push the compacted soil into the collar space of the compaction mould. A displacement rate of 5.0 mm/min is used in this study. The loading machine includes a 5 kN load cell to measure the applied load during the extrusion process. The platen of the load cell was designed to have nearly the same or slightly less than the mould diameter to ensure distributing equal load on the soil surface without penetration.

Figure 3.6 Testing model of shear interfacial adhesion.

Therefore, the testing process involves shearing the soil against the internal surface of the compaction mould by applying a vertical load, as shown in Fig. 3.6. The soil protrusion and displacement should be equal to confirm that the extrusion load does not apply further compression on the compacted soil in the compaction mould, as shown in Fig. 3.7. During the loading process, the displacement and load are recorded and plotted as a load-displacement curve, as shown in Figs 3.8, 3.9, and 3.10, for different types of soil specimens. The peak of the load-displacement curve shows the maximum adhesion capacity of the interface surface between the compacted soil and the internal wall of the compaction mould.

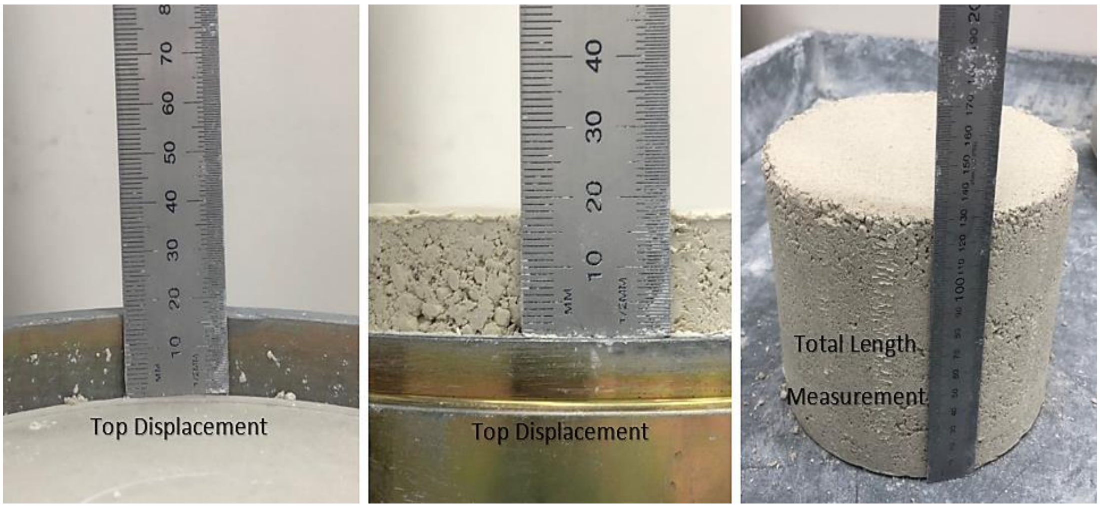

Figure 3.7 Measurement of soil displacement after testing the adhesion.

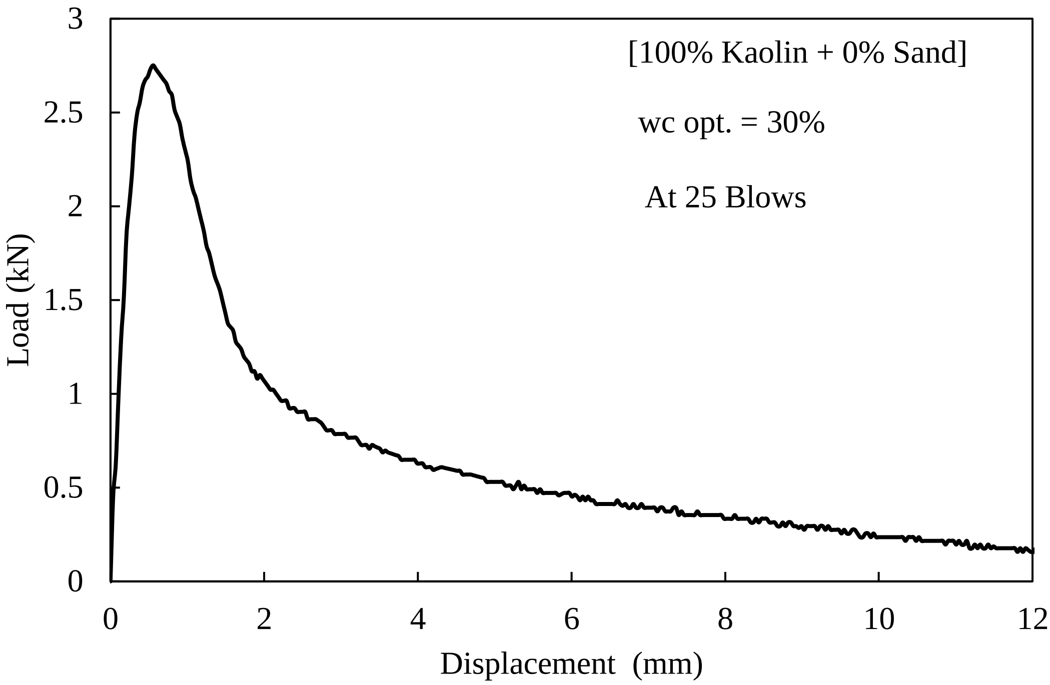

Figure 3.8 Adhesion curve of kaolin clay contains no sand.

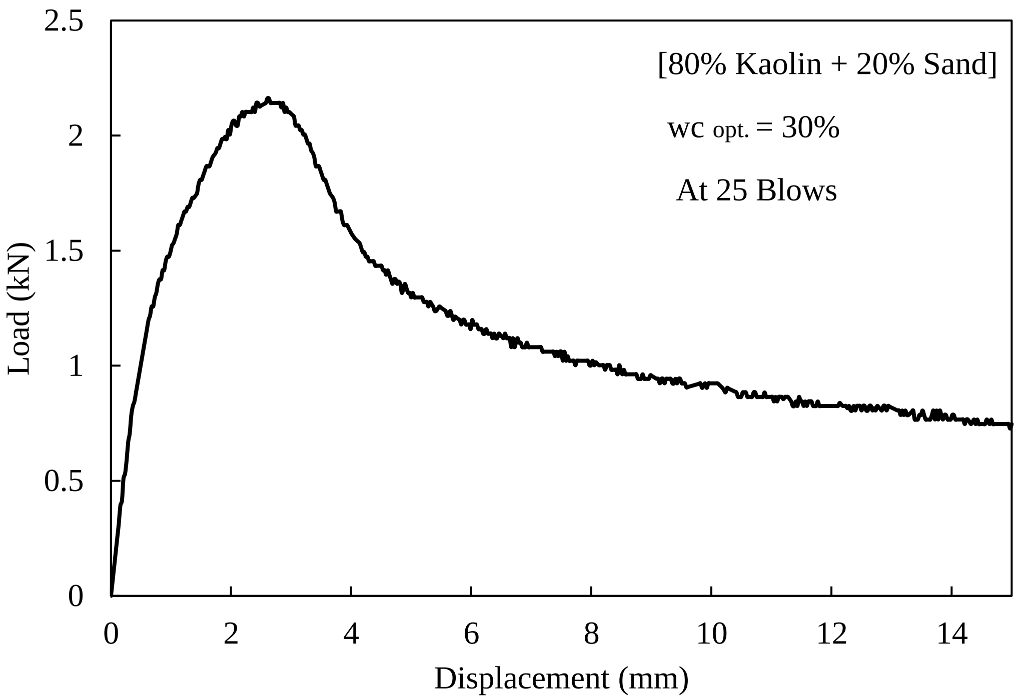

Figure 3.9 Adhesion curve of kaolin clay contains 20% sand.

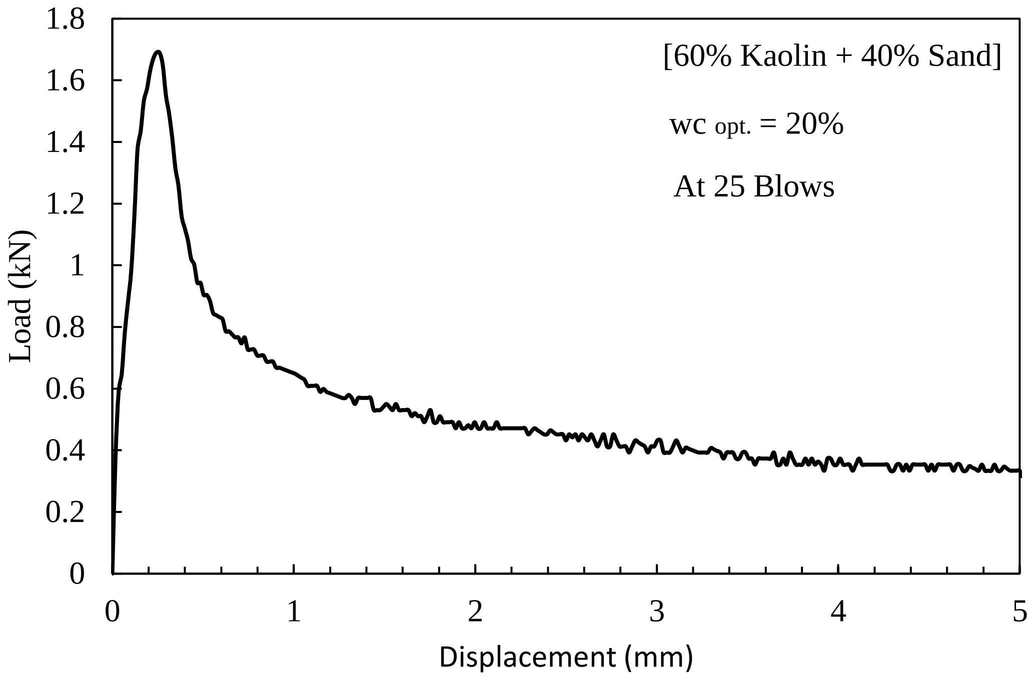

Figure 3.10 Adhesion of kaolin clay contains 40% sand.

The soil-mould interfacial adhesion can be determined using the following formula:

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

where:

α: interfacial adhesion in kPa

P: peak load in kN

A: internal surface of the mould in m^2

Several tests were repeated under the same conditions to confirm the repeatability of the proposed testing method. The results in Fig. 3.11 confirm the repeatability of the test results using the testing method proposed in this study.

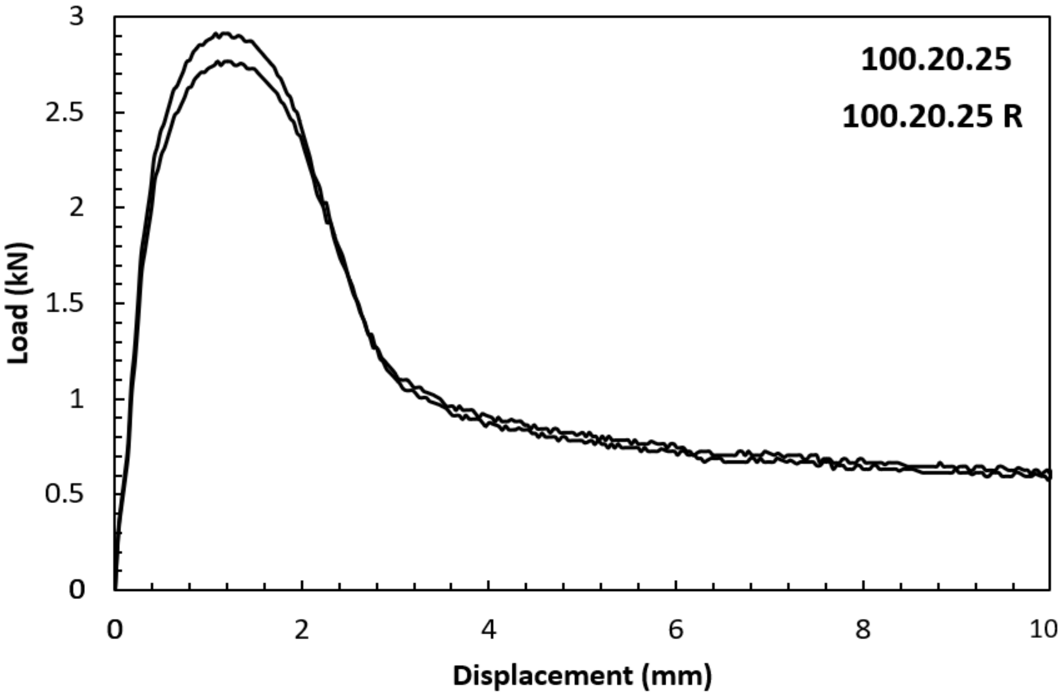

Figure 3.11 Repeatability of tests (100% kaolin, wc=20%, no. of blows =25).

CHAPTER 4:

Results and Discussion

4.1 Introduction

This chapter presents and discusses the results of the experiments conducted in this study. It presents the compaction curves of the tested soils and the factors that influence them. It also shows the test results of the shear adhesion tests. It discusses the observed shear adhesion behaviour in terms of the effect of moisture content, dry density and soil mineralogy. The obtained results were used to develop three-dimensional graphs that show the coupling effects of the factors that control soil shear adhesion behaviour.

4.2 Compaction

Soil compaction is the process of packing soil particles which results in removing the air voids from the soil which consequently leads to an increase in dry density, as shown in Fig. 4.1. The scale that the compaction degree is measured by is the soil's dry density, which depends on the moisture content of the soil. It also depends on the compaction energy, which is determined by the weight of the rammer and the number of applied blows. Generally, when the number of blows increases, dry density increases accordingly, as shown in Fig. 4.2. As a result of this compaction, the maximum dry density of soil can be achieved at a specific moisture content which is called the optimum moisture content (OMC). The OMC varies based on the type of soil and compaction energy (Head, 1980).

The relationship between dry density and moisture content is known as the compaction curve. This curve can take different shapes and values based on the characteristics of the compacted soil (Head, 1980). Clayey soils have a compaction curve of one peak, unlike sandy soils which tend to have double peaks on a curve. The soil mineralogy and the percentage of water content in the soil play a role in influencing the compaction process and its results.

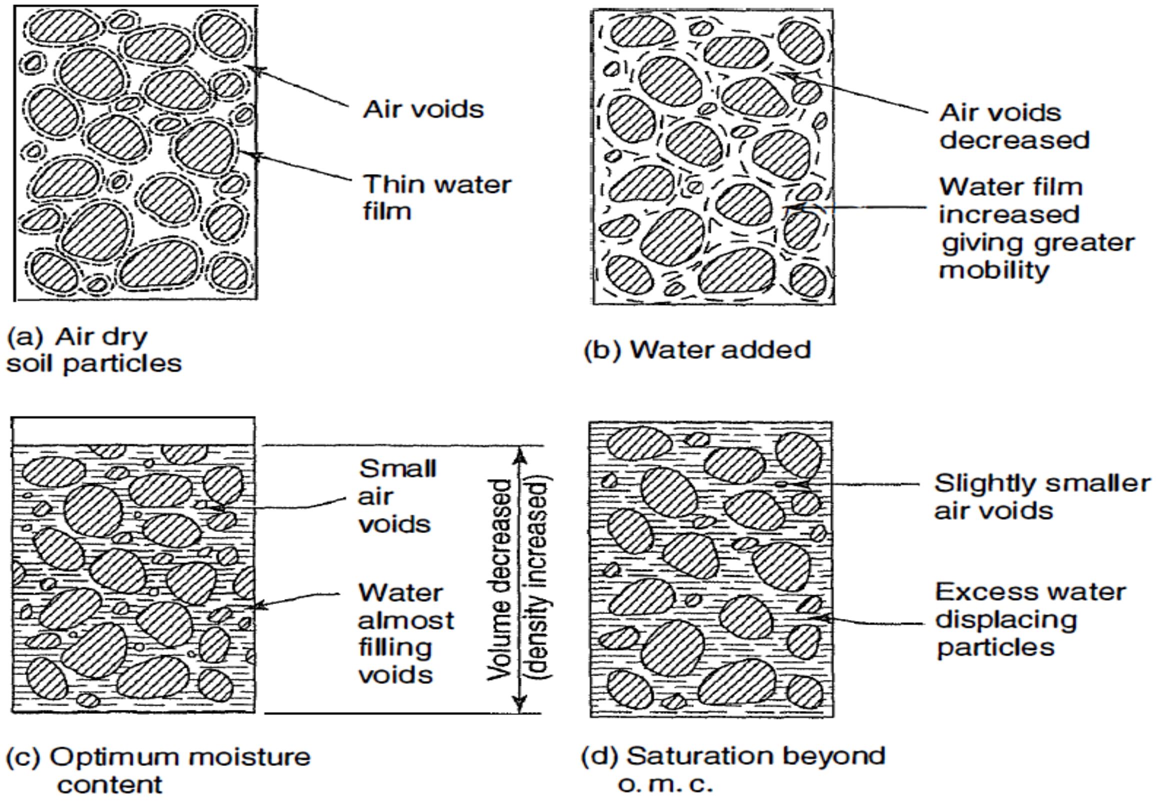

Figure 4.1 Representation of compaction stages and air voids in soil samples (Head 1980).

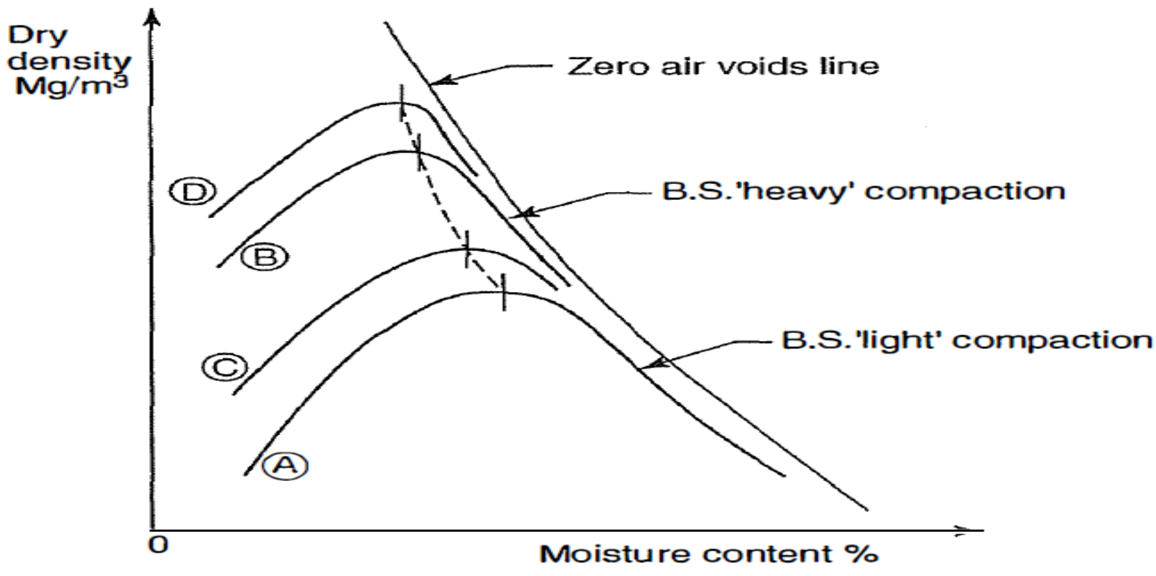

Figure 4.2 Compaction curves for various compaction degrees (Head 1980).

The three types of soil that are tested in this research have different compaction curves under the same conditions, as shown in Figs. 4.3,4.4, and 4.5, and this leads to different values of dry densities and OMC. The presence of sand in kaolin affects the values of dry density and OMC as explained in the following sections.

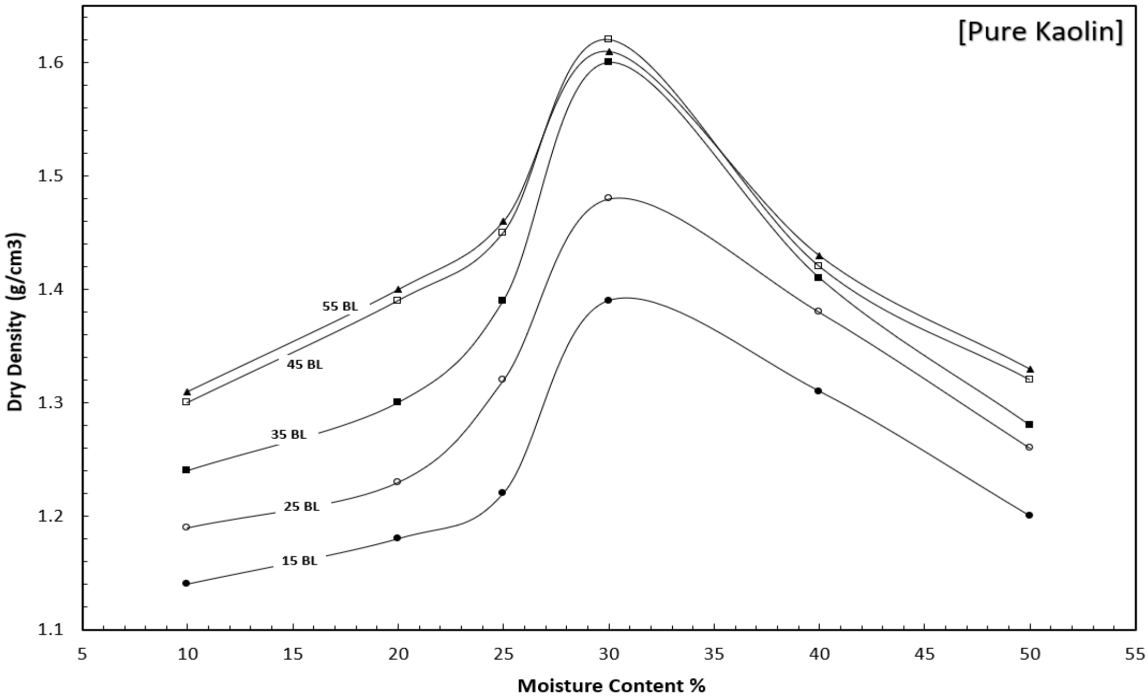

Figure 4.3 Compaction curve of kaolin at different compaction efforts.

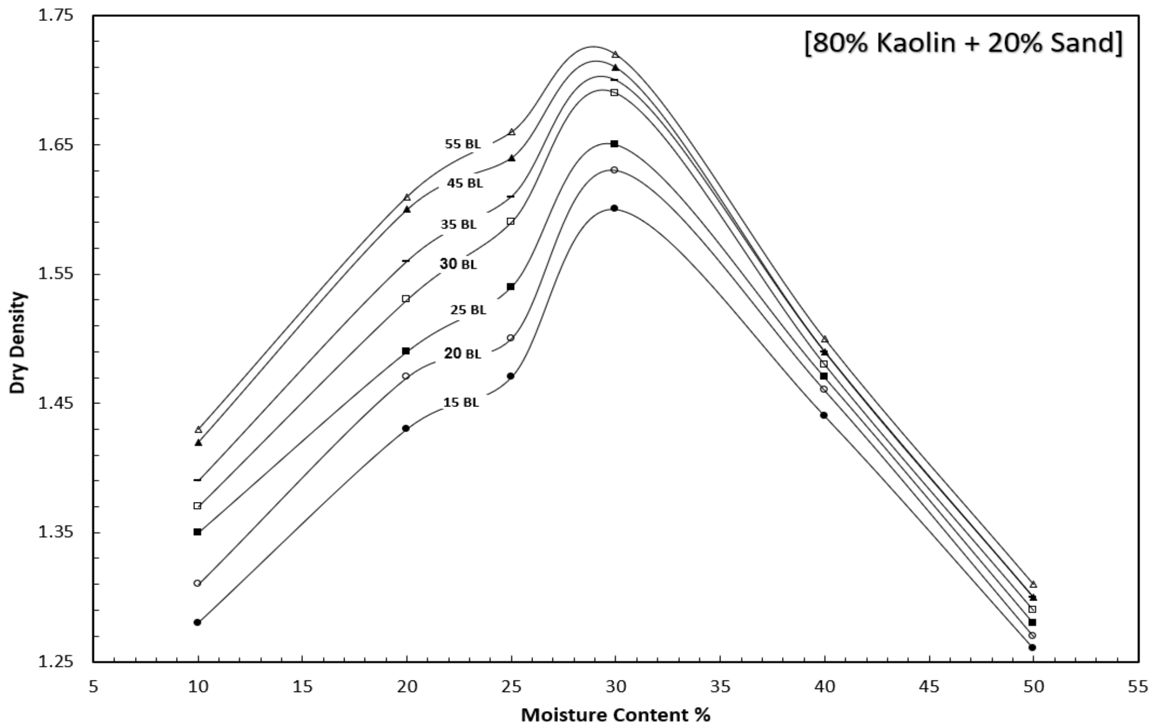

Figure 4.4 Compaction curve of kaolin with 20% sand at different compaction efforts.

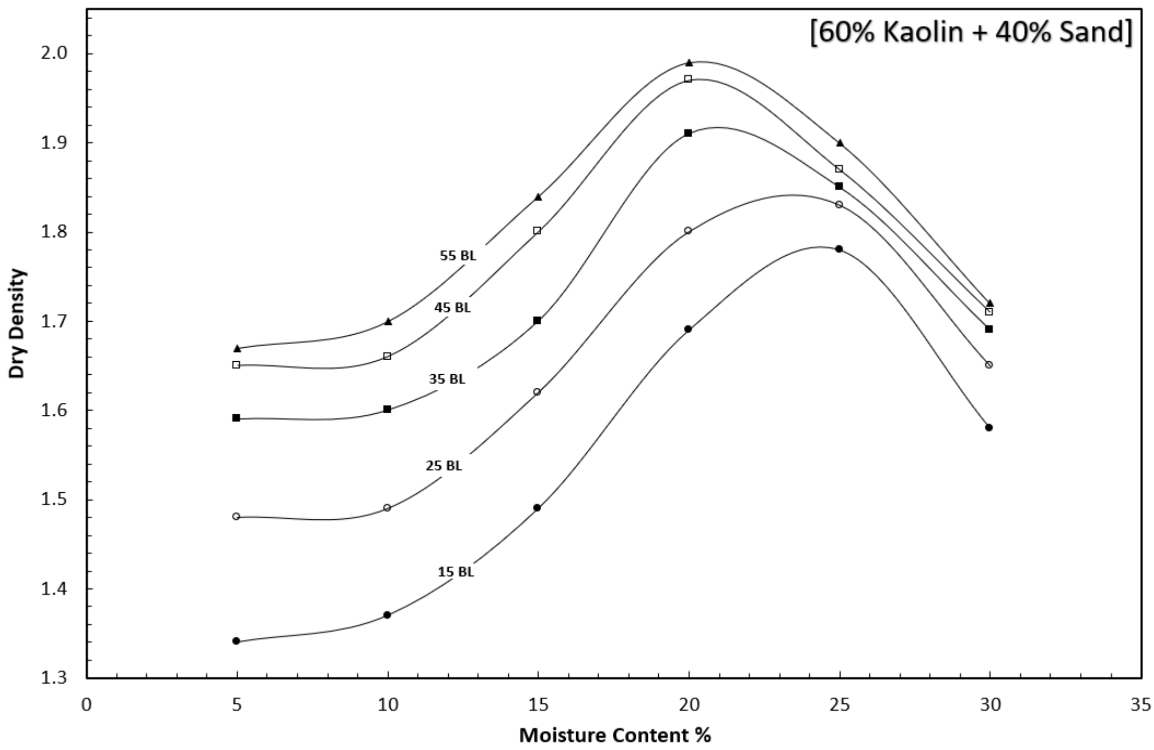

Figure 4.5 Compaction curve of kaolin mixed with 40% sand at different compaction efforts.

In this research, the water content of the soil samples ranges from 5% to 50% to suit the different soil compositions in this study, as shown in Fig. 4.6. Pure kaolin has higher OMC compared to the other types of soils where OMC decreases as the percentage of sand increases. This behaviour can be attributed to the higher specific surface area of kaolin compared to sand. Consequently, less water content is required to coat the soil particles as the sand content of the soil mixture increases. The compaction results also show that maximum dry density increases as the sand content increases.

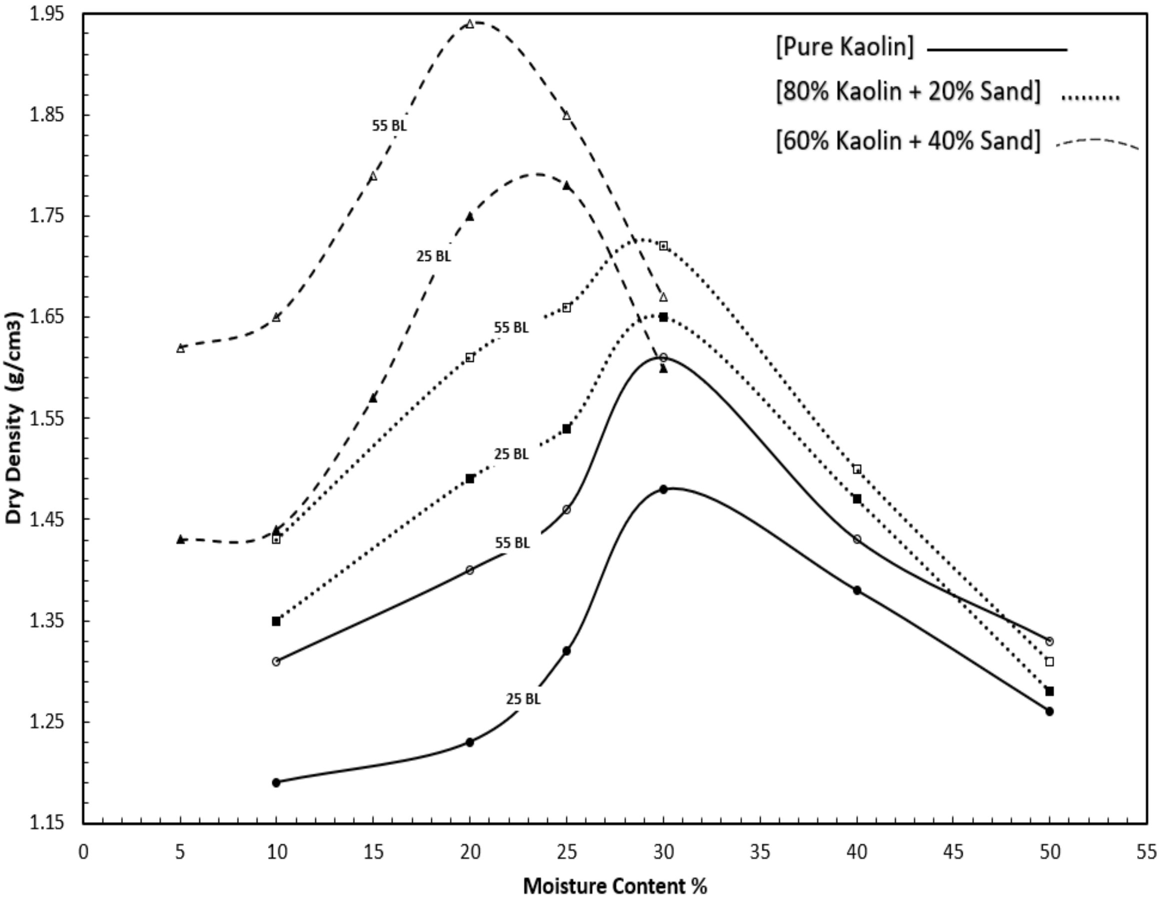

Figure 4.6 Compaction curves at standard and maximum densities for all soil compositions.

4.2.1 Effect of mineralogy on compaction

Soil mineralogy plays a vital role in specifying the maximum dry density and optimum moisture content. Each soil has unique characteristics which define how the soil behaves when compacted. The grain size distribution is the main factor that controls the process of compaction of coarse-grained soils. Well-graded soils can achieve higher maximum dry density by compaction compared to poorly graded soils (Soil Compaction Handbook, 2011).

The effect of sand content on the dry density of the kaolin-sand mixture at different moisture contents levels are shown in Figs. 4.7, and 4.8 for standard and modified compacting energy levels, respectively. Dry density increases as sand content increases for all moisture content on the dry side of the compaction curve (10% and 20%). However, on the wet side (wc=30%), the effect of adding more sand is different. Up to a certain sand content, dry density slightly increases, but beyond this particular value, dry density decreases. This behaviour can be explained in terms of the effect of sand content on OMC. OMC decreases as sand content increases, therefore the degree of saturation of the compacted specimen at wc=30% increases. Consequently, the compactability of the soil specimen decreases so dry density decreases.

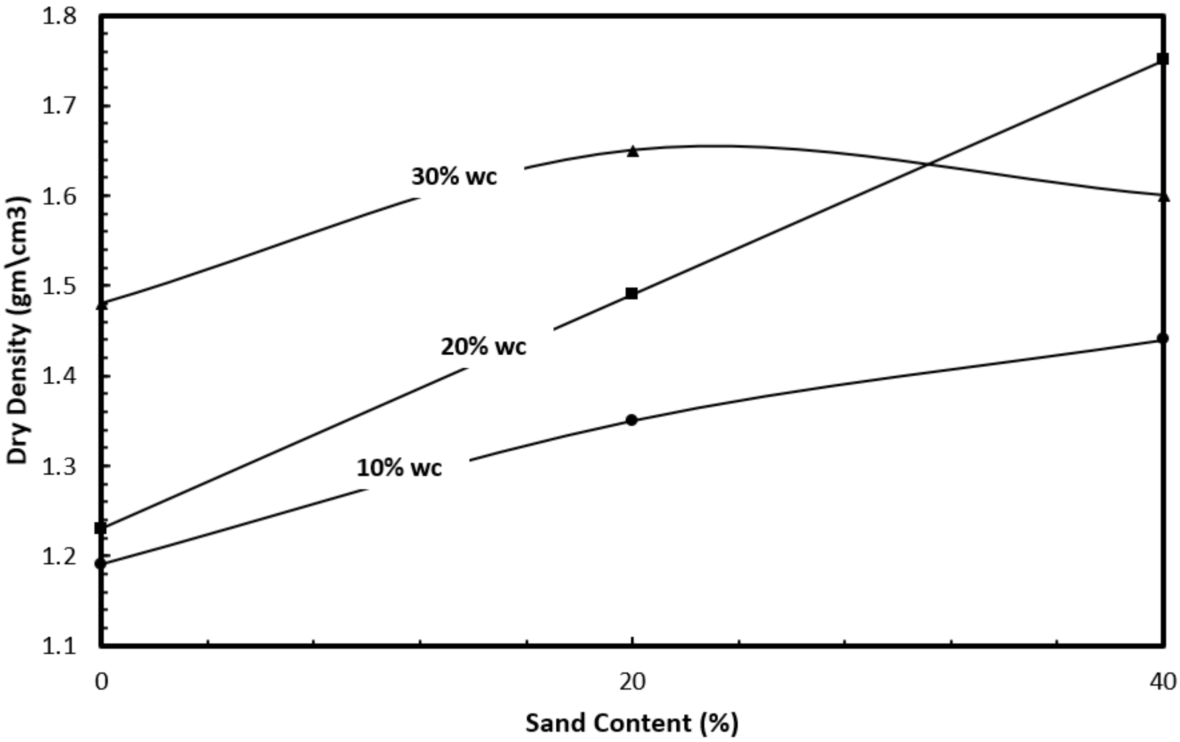

Figure 4.7 Effect of sand content on dry density at different moisture contents under standard compaction (25 Blows) .

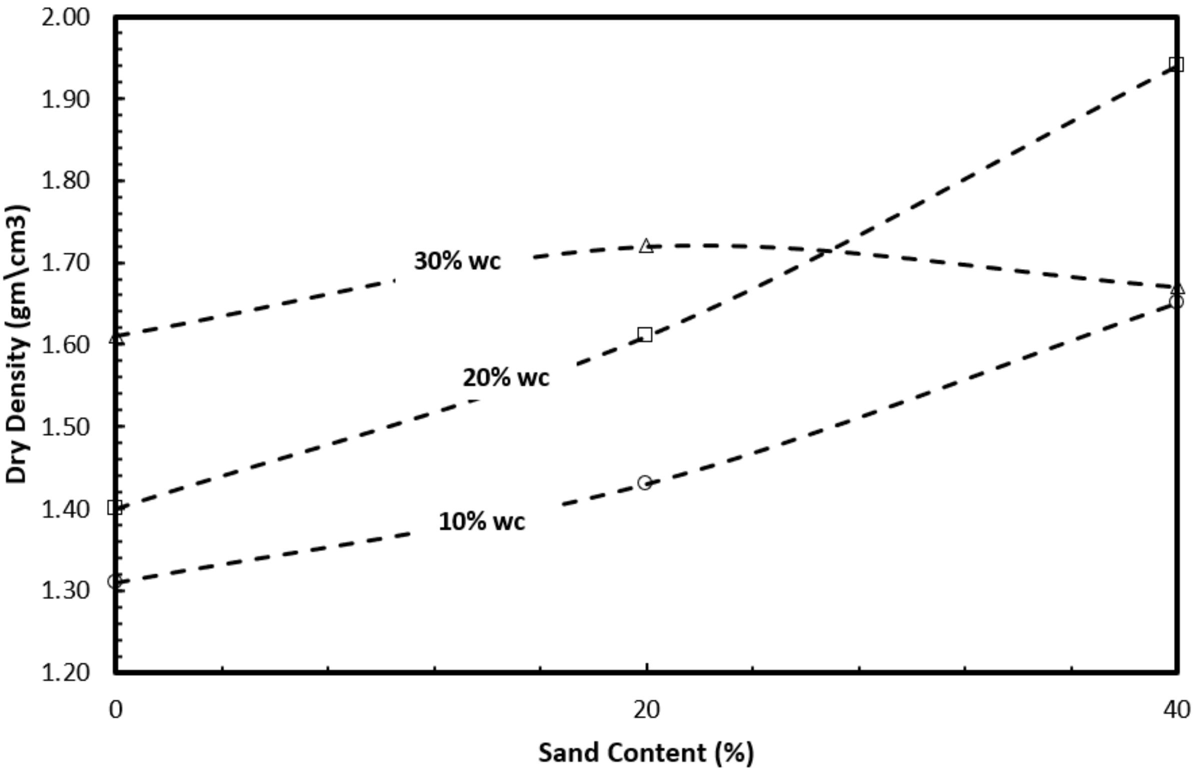

Figure 4.8 Effect of sand content on dry density at maximum compaction (55 Blows).

4.2.2 Effect of compaction energy

It is well known that the outcome of compaction in terms of maximum dry density and OMC relies on the amount of compaction energy applied to the soil, as shown in Fig. 4. 9. Figures 4.10 and 4.11 show the effect of the number of blows (compaction energy) on dry density at different water content levels. These figures show how the dry density of soil increases with an increase in the number of blows until a specific limit that depends on the soil composition and water content. For kaolin with water contents in the range of 10% to 25%, maximum dry density was achieved at 45 blows, as shown in Fig. 4.10. Beyond these limits, increasing the number of blows has an insignificant effect on dry density. However, at wc= 5%, kaolin shows improvement in dry density up to 55 blows. Similar behaviour was also observed for the kaolin-sand mixture soil, as shown in Fig. 4.11.

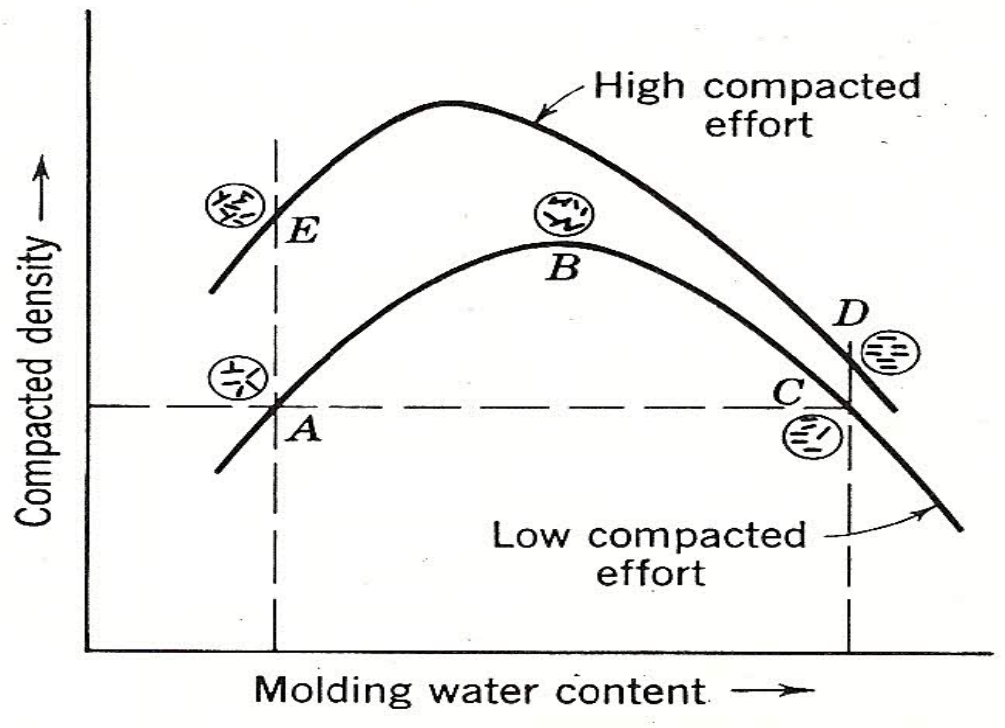

Figure 4.9 Effect of compaction effort on OMC of compacted soil (Abdul-Sahib T Al-Madhhachi et al. 2012).

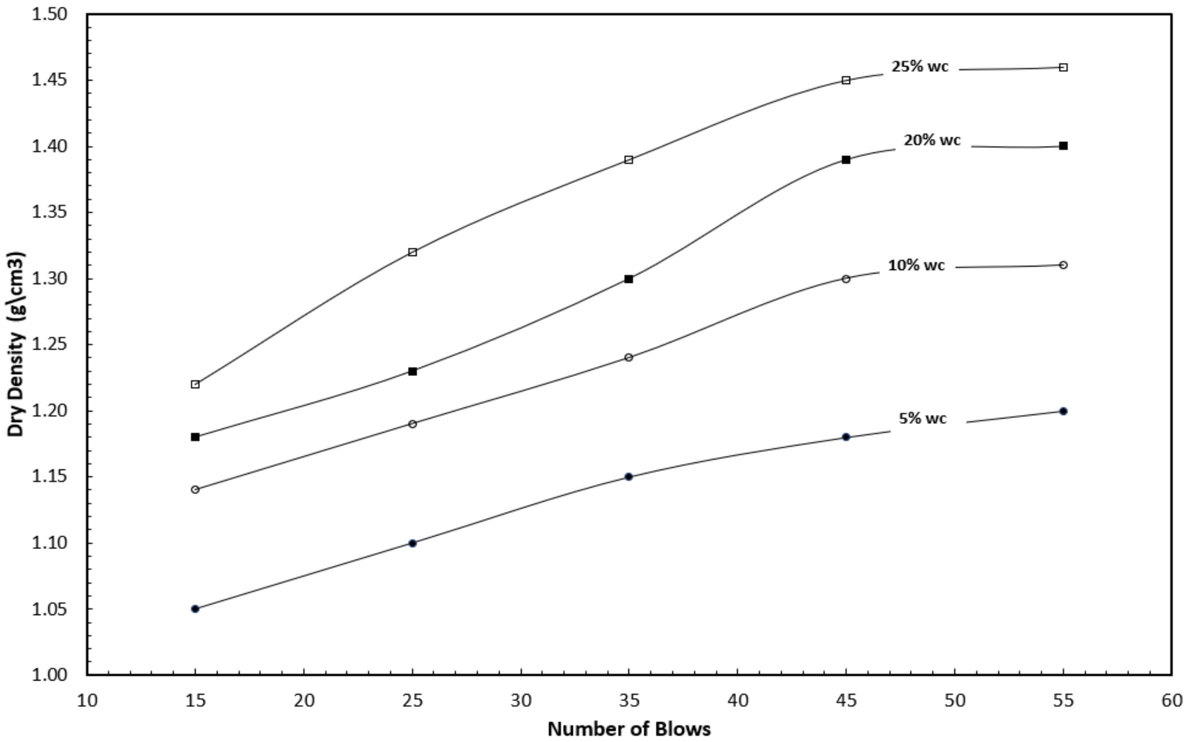

Figure 4.10 Effect of compaction energy on dry density at different moisture contents of kaolin.

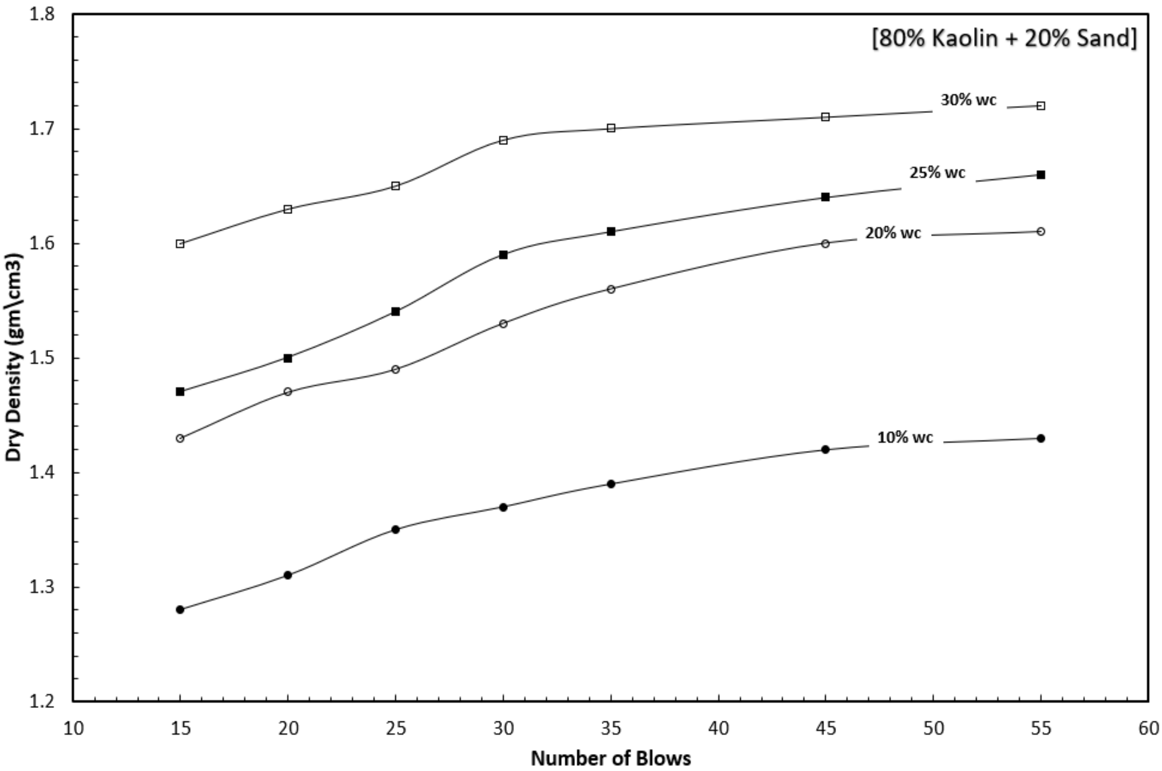

Figure 4.11 Effect of compaction energy on dry density at different moisture contents of [kaolin + 20% sand].

4.3 Adhesion

The value of shear adhesion at the interface relies on factors that relate to the properties of soil/continuum surface and testing conditions (Jia, 2004). This research focussed on the effect of compacted soil properties on shear adhesion between soil and the modified compaction mould, which is made of brass. The soil properties considered in this study are moisture content, dry density and soil composition in terms of the mixture ratio of sand and kaolin.

4.3.1 Effect of moisture content on soil shear adhesion

Moisture content has a significant impact on soil adhesion. As indicated by Jancsecz (1991), soil adhesion is a function of moisture content, and the maximum adhesion is expected to occur at a water content between the liquid and the plastic limits.

4.3.1.1 Pure Kaolin

Figure 4.12 and Table 4.1 show how the shear adhesion of compacted kaolin changes with the moisture content and passes through four stages. Two of them fall on the dry side of the compaction curve, whereas the other two are on the wet side of the compaction curve. The optimum moisture content of this soil is about 30%. These stages of adhesion are explained as follows:

1st stage: At the dry side of the compaction curve and with low moisture content (10% to 20%), adhesion decreases as moisture content increases. As the moisture content increases, the matric suction that bonds the soil particles to the internal surface of the compaction mould decreases. So, adhesion decreases.

2nd stage: At the dry side of the compaction curve and with high moisture content (20% to 30%), adhesion becomes constant as the water content increases in this range. This behaviour could be attributed to the expected balance between the effect of the increase in dry density, which should increase adhesion, and the expected decrease of matric suction as the moisture content increases in this water content range, which should decrease adhesion.

3rd stage: At the wet side of the compaction curve and with low moisture content (30% to 40%), adhesion decreases as moisture content increases. The soil is almost fully saturated at this stage. So, the matric suction role is almost null. In this stage, as the moisture content increases, dry density decreases. Consequently, the contact surface area of the soil particles and the mould surface decreases. So, adhesion decreases.

4th stage: At the wet side of the compaction curve and with very high moisture content (> 40%), adhesion remains constant as moisture content increases. Matric suction is almost zero in this stage. It is believed that the decrease of dry density in this stage does not affect shear adhesion as there is no direct contact between the soil particles and the compaction mould.

Table 4.1 Analysis of (Pure Kaolin) adhesion behaviour under the effect of some factors at standard compaction.

	Dry side		Wet Side	
	Stage 1	Stage 2	Stage 3	Stage 4
Wc %	[10% ~ 20%]	[20% ~ 30%]	[30% ~ 40%]	[> 40%]
γ_d (g/cm^3)	Very Small ↑ (0.04)	Large ↑ (0.25)	Very Small ↓ (0.09)	Moderate ↓ (0.13)
Su (pF)	Moderate ↓ (0.28)	Large ↓ (0.71)	Large ↓ (0.53)	Moderate ↓ (1.00)
Sr %	Large ↑ (24%)	Large ↑ (58%)	Moderate ↑ (15%)	Small ↑ (2%)
α (kPa)	Large ↓ (18)	Plateau — (No change)	Large ↓ (38)	Very small ↓ (3 kPa)

Figure 4.13 shows the contour plot of the test results. It represents the plot of the coupling effect of dry density and moisture content on shear adhesion behaviour. The upper boundary of the shaded area represents the results of 55 blows, and the lower boundary represents the results of 15 blows. The shaded area represents the possible shear adhesion of this soil in wc-dry density domain where the dotted line represents the results of the soil specimen compacted by 25 blows (standard compaction). These results show that at a constant dry density, an increase in moisture content decreases shear adhesion. However, the rate of shear adhesion reduction depends on the dry density level as it increases as dry density increases. Also, it is noted that moisture content has a significant effect on adhesion up to wc=40%. However, beyond this moisture content level, increasing the moisture content does not affect shear adhesion regardless of the dry density level.

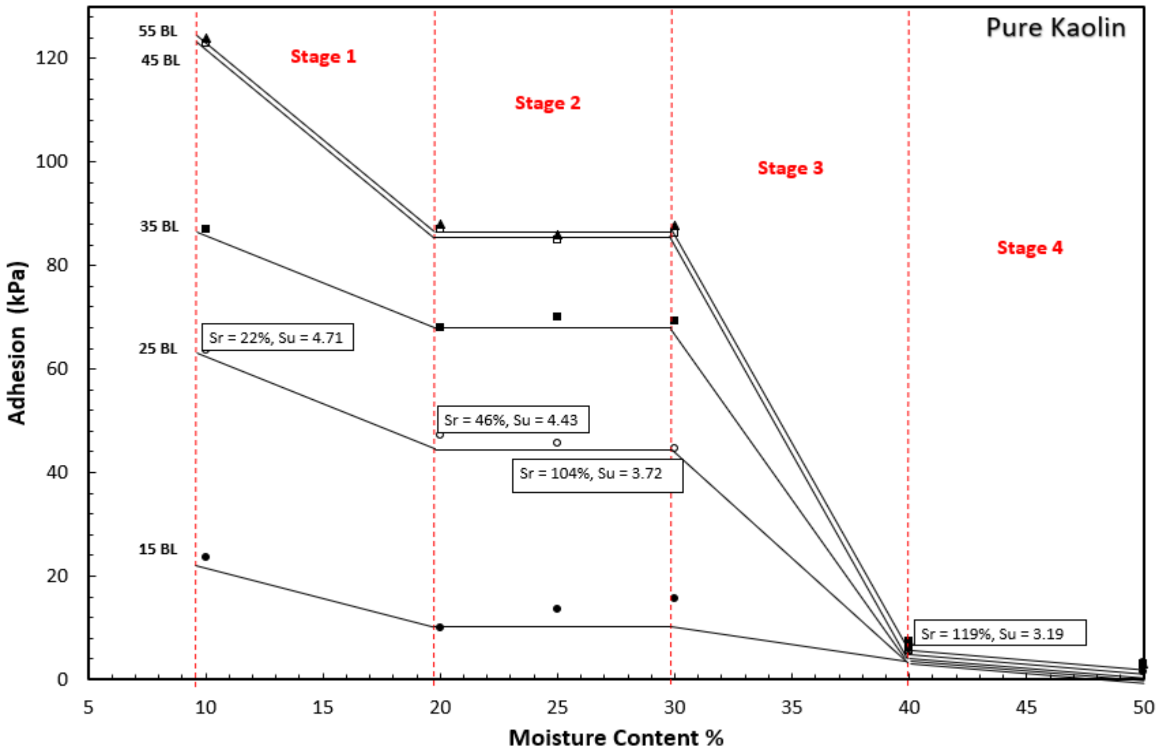

Figure 4.12 Effect of moisture content on interfacial adhesion of pure kaolin

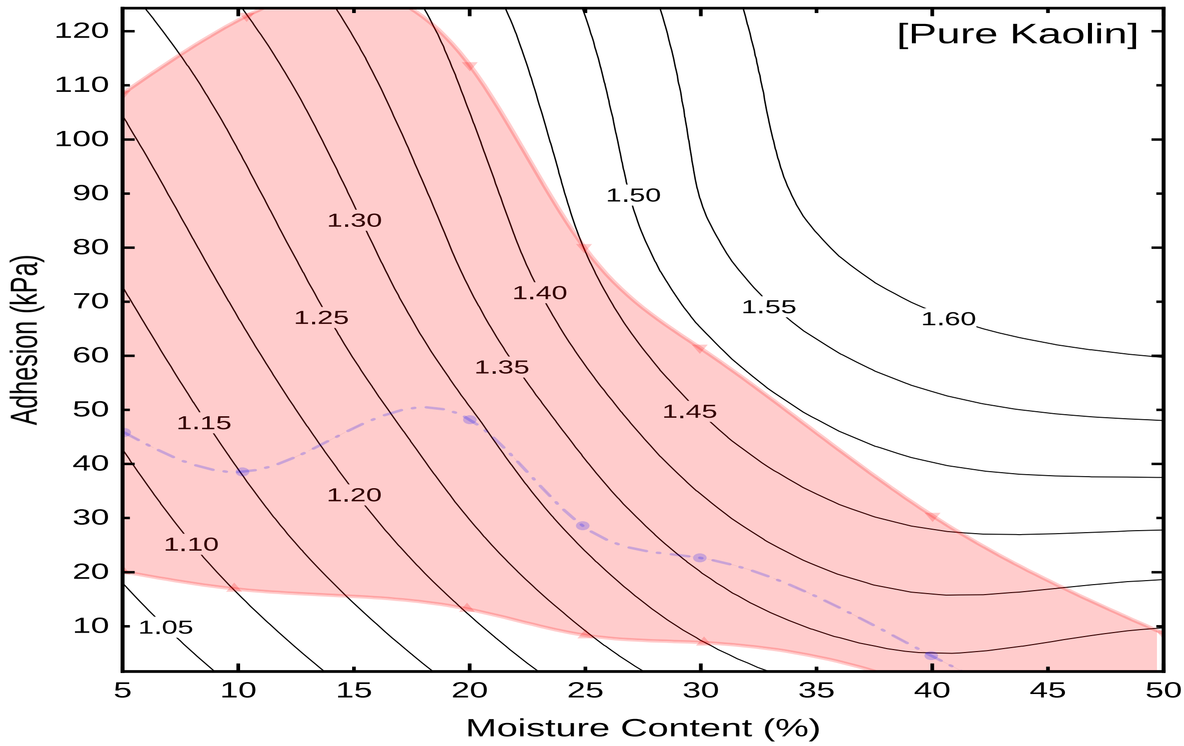

Figure 4.13 [3-D graph] effect of dry density and moisture content on the adhesion of Pure Kaolin.

4.3.1.2 [80% kaolin + 20% sand]

Figure 4.14 and Table 4.2 show that the adhesion of this soil type also has four stages within the tested moisture content domain. The optimum moisture content of this soil is about 30%, which is similar to OMC of kaolin. However, due to the existence of sand, the shear adhesion behaviour of the first two stages (dry side) of this soil is different from the observed behaviour of kaolin. Furthermore, for soil compacted using low compaction energy, increasing the moisture content on the dry-side does not affect adhesion. The four stages are described as follows:

1st stage: At the dry side and with low moisture content (10% to 20%), adhesion increases as moisture content increases. This behaviour could be attributed to the fact that the increase in the dry density in this zone has more effect on adhesion than the expected reduction in the soil suction as the moisture content increases.

2nd stage: At the dry side and with high moisture content (20% to 30%), adhesion decreases as moisture content increases. This behaviour could be attributed to the decrease in soil suction, as the moisture content increases in this zone has more effect on adhesion than the increase in the dry density as moisture content increases.

3rd stage: At the wet side of the compaction curve and with low moisture content (30% to 40%), adhesion decreases as moisture content increases. The soil is almost fully saturated at this stage. So, the role of matric suction is almost null. In this stage, as the moisture content increases, dry density decreases. Consequently, the contact surface area of the soil particles and the mould surface decreases. So, adhesion decreases.

4th stage: At the wet side of the compaction curve and with very high moisture content (> 40%), adhesion remains constant as the moisture content increases. Matric suction is almost zero in this stage. It is believed that the decrease of dry density in this stage does not affect shear adhesion as there is no direct contact between the soil particles and the compaction mould.

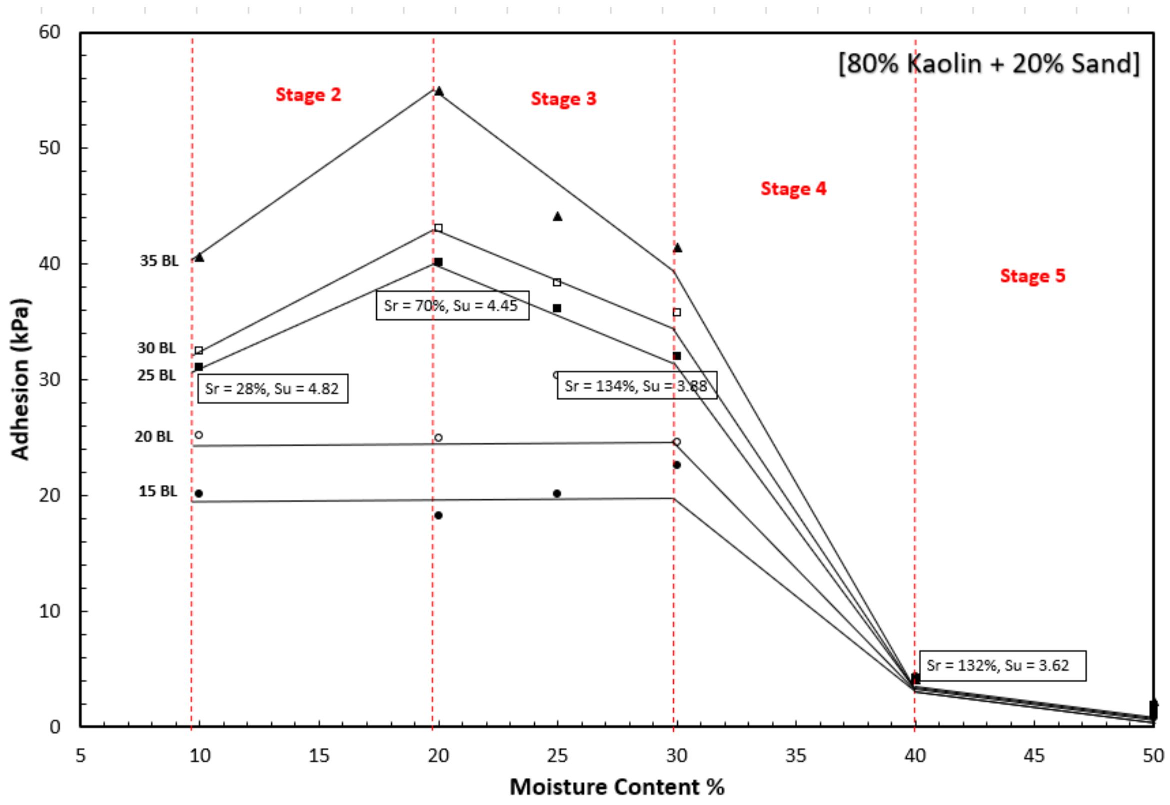

Figure 4.14 Effect of moisture content on interfacial adhesion of kaolin mixed with 20% Sand.

Table 4.2 Analysis of (80% Kaolin + 20% Sand) adhesion behaviour under the effect of certain factors at standard compaction.

	Dry side		Wet side	
	Stage 1	Stage 2	Stage 3	Stage 4
Wc %	[10% ~ 20%]	[20% ~ 30%]	[30% ~ 40%]	[> 40%]
γ_d (g/cm^3)	Large ↑ (0.14)	Large ↑ (0.16)	Large ↓ (0.19)	Large ↓ (0.18)
Su (pF)	Moderate ↓ (0.36)	Large ↓ (0.61)	Moderate ↓ (0.22)	Moderate ↓ (0.43)
Sr %	Large ↑ (42%)	Large ↑ (64%)	Plateau — (No change)	Plateau — (No change)
α (kPa)	Small ↑ (9)	Small ↓ (6)	Large ↓ (29)	Large ↓ (2)

Figure 4.15 shows a contour plot of the test results. It shows the plot of the coupling effect of dry density and moisture content on the shear adhesion behaviour. The upper boundary of the shaded area represents the results of 55 blows and the lower boundary represents the results of 15 blows. This shaded area represents the possible shear adhesion of this soil in wc-dry density domain. The results show that at a constant dry density, increasing the moisture content decreases shear adhesion. However, the rate of shear adhesion reduction is almost independent of the dry density level within the dry side range (OMC<30%). Also, it is noted that moisture content has a significant effect on adhesion up OMC. Beyond OMC, increasing the water content has no effect on adhesion regardless of the dry density level.

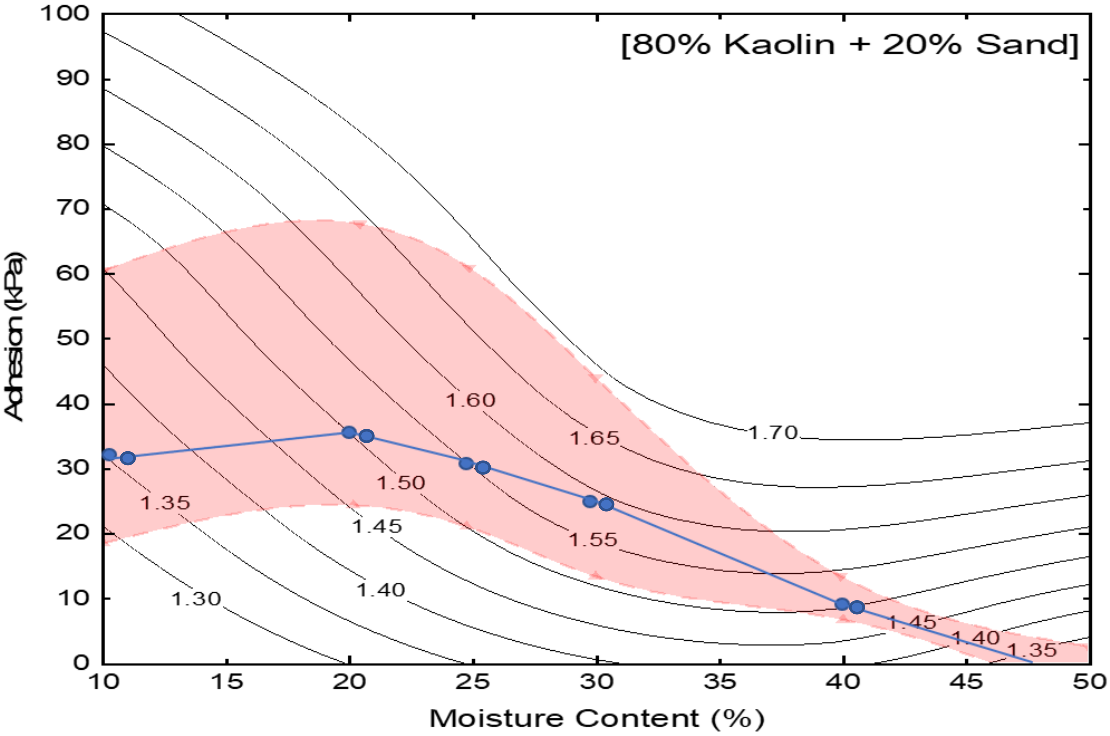

Figure 4.15 [3-D graph] effect of dry density and moisture content on adhesion of 20% Sandy Kaolin.

4.3.1.3 [60% kaolin + 40% sand]

Figure 4.16 and Table 4.3 show that the adhesion of this soil type also has four different stages. The optimum moisture content of this soil is about 20%. The available results show that the adhesion in the wet-side range (wc>OMC) is almost similar, regardless of the percentage of sand. However, the adhesion behaviour in the dry side (wc<OMC) shows that by increasing the sand content, adhesion behaviour changes. In fact, this behaviour at the dry side could be attributed to the matric suction role that is only available on the dry side. For the wet side, the matric suction is almost zero. The higher adhesion observed at low water content for 40% sand compared to 20% sand can be explained in terms of the possible mechanical interlocking effect between the sand and the roughness of the mould wall surface which could increase adhesion resistance, especially when matric suction is high (low water content). The four stages in this soil mix are as follows:

1st stage: At the dry side of the compaction curve and with low moisture content (5% to 10%), adhesion decreases as moisture content increases. This is because when moisture content increases, the matric suction that bonds the soil particles to the internal surface of the compaction mould decreases.

2nd stage (a): At the dry side of the compaction curve and with high moisture content (10% to 15%), adhesion increases as moisture content increases. This behaviour could be attributed to the fact that the increase in the dry density in this zone has more effect on adhesion that the expected reduction in the soil suction as the moisture content increases.

2nd stage (b): At the dry side of the compaction curve and with high moisture content (15% to 20%), adhesion decreases as moisture content increases. This behaviour can be attributed to the decrease in the soil suction because as moisture content increases in this zone, it has more effect on adhesion than an increase in dry density as moisture content increases.

3rd stage: At the wet side of the compaction curve and with low moisture content (20% to 25%), adhesion decreases as moisture content increases. The soil is almost fully saturated at this stage. So, the matric suction role is almost null. In this stage, as moisture content increases, dry density decreases. Consequently, the contact surface area of the soil particles and the mould surface decreases. So, the adhesion decreases.

4th stage: At the wet side of the compaction curve and with very high moisture content (> 25%), adhesion remains constant as moisture content increases. Matric suction is almost zero in this stage. It is believed that the decrease of dry density in this stage does not affect shear adhesion as there is no direct contact between the soil particles and the compaction mould.

Table 4.3 Analysis of (60% kaolin + 40% sand) adhesion behaviour under the effect of certain factors at standard compaction.

	Dry side			Wet side	
	Stage 1	Stage 2a	Stage 2b	Stage 3	Stage 4
Wc %	[5% ~ 10%]	[10% ~ 15%]	[15% ~ 20%]	[20% ~ 25%]	[> 25%]
γ_d (g/cm^3)	Very Small ↑ (0.01)	Large ↑ (0.13)	Large ↑ (0.17)	Large ↓ (0.13)	Large ↓ (0.17)
Su (pF)	Moderate ↓ (0.27)	Small ↓ (0.12)	Large ↓ (0.60)	Plateau — (No change)	Plateau — (No change)
Sr %	Moderate ↑ (15%)	Large ↑ (26%)	Large ↓ (49%)	Large ↑ (29%)	Small ↓ (5%)
α (kPa)	Large ↓ (20)	Small ↑ (10)	Large ↓ (16)	Large ↓ (20)	Small ↓ (3%)

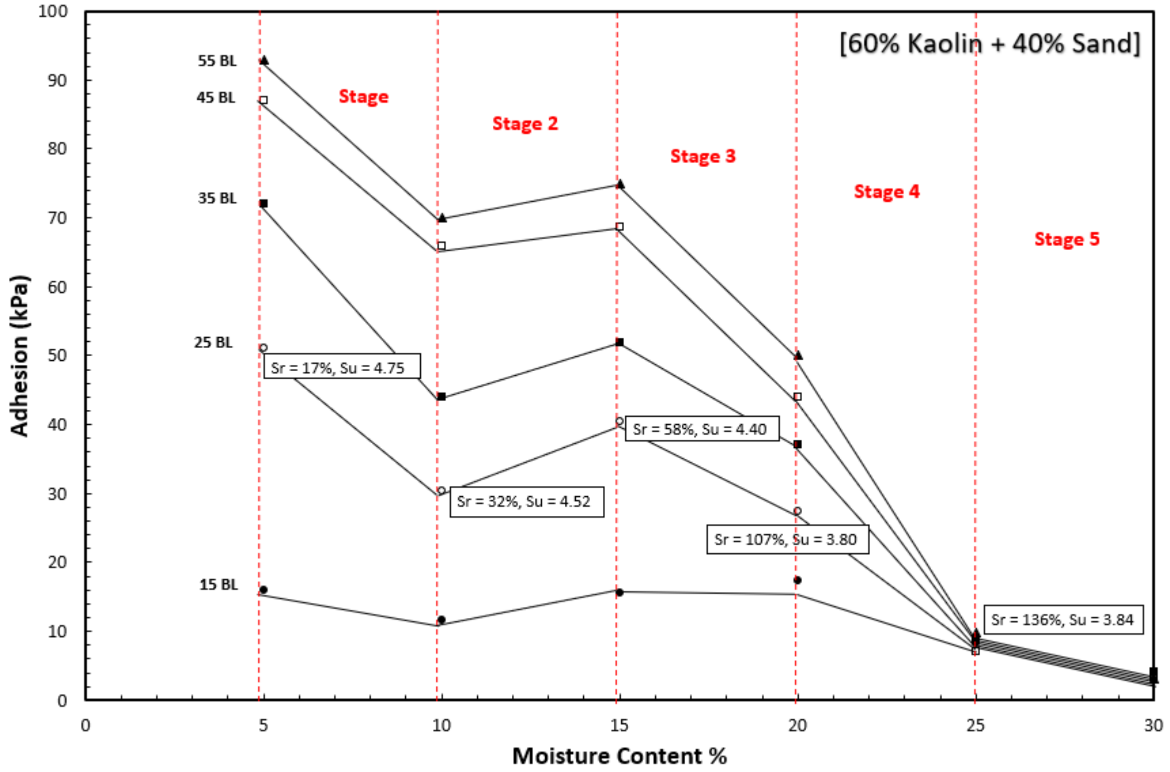

Figure 4.16 Effect of moisture content on interfacial adhesion of kaolin mixed with 40% sand.

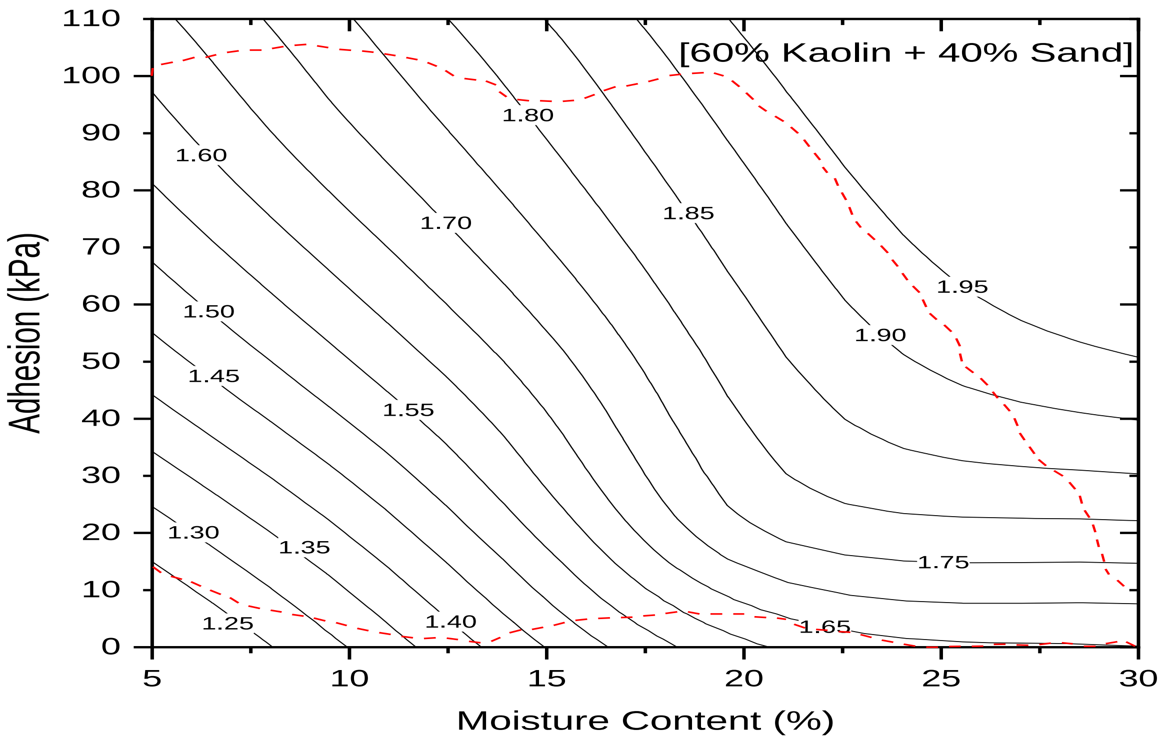

Figure 4.17 [3-D graph] effect of dry density and moisture content on adhesion of 40% sandy kaolin.

4.3.2 Effect of dry density on soil adhesion

Figure 4.18 illustrates that the relationship between dry density and adhesion is linear at the dry side of the curve for the three tested soil groups. However, at the wet side, where the moisture content is high, the effect of dry density on soil adhesion becomes very low and negligible. In general, the results show that the effect of dry density changes on adhesion decreases as moisture content increases. The increase of soil adhesion as dry density increases can be attributed to the expected increase in the contact area as dry density increases. Increasing dry density via compaction brings soil particles closer and creates a larger contact surface area between the soil and the mould. A large contact area leads to large interfacial soil adhesion. However, increasing the moisture content decreases adhesion as the matric suction of the soil decreases.

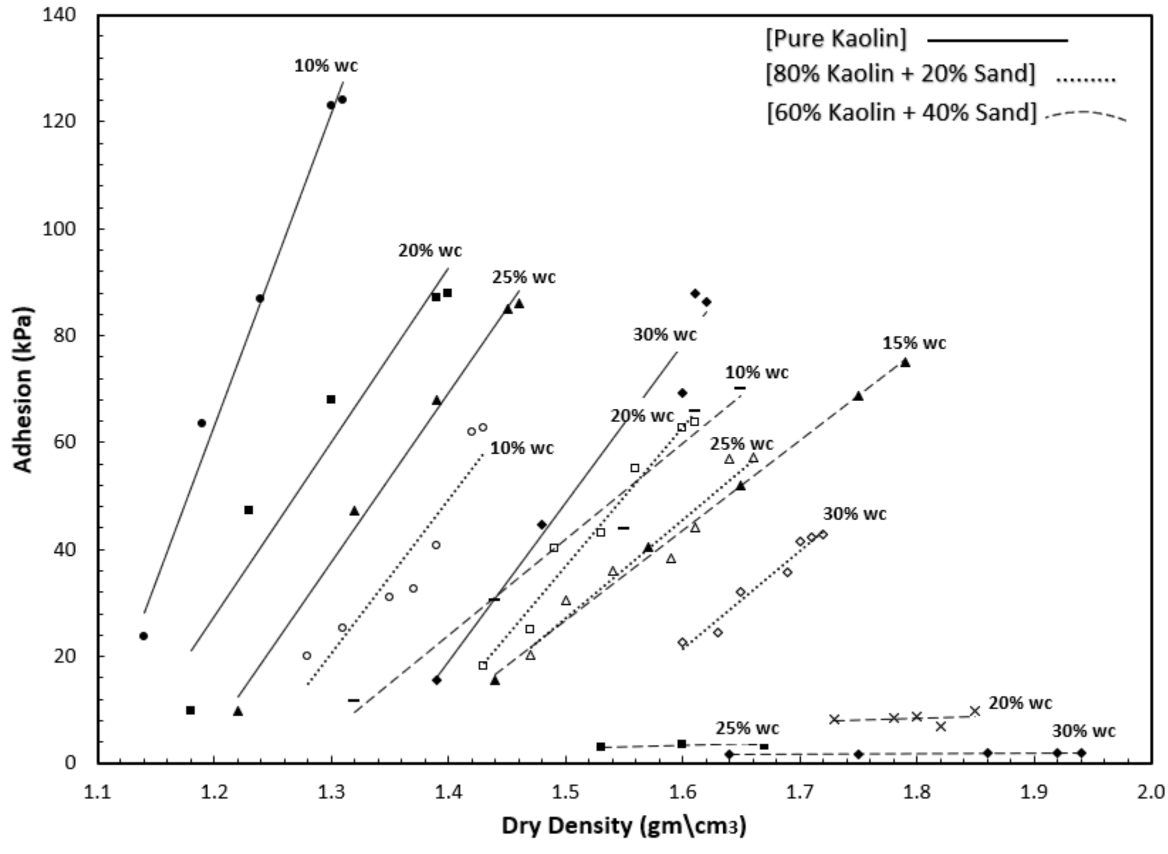

Figure 4.18 Comparison of the effect of dry density on interfacial adhesion of all the studied soil compositions.

The following formula is used to calculate the rate of adhesion change per dry density change:

$$R = \frac{\Delta\,\alpha}{\Delta\,\gamma d}$$

where:

$\Delta\,\alpha$ is the slope of the adhesion curve in Fig. 4.18.

$\Delta\,\gamma_d$ is the corresponding dry density values.

The rate R was plotted for the different types of soils,and the moisture content tested in this study, as shown in Fig. 4.19. The results indicate that as sand content and water content increases, R decreases.

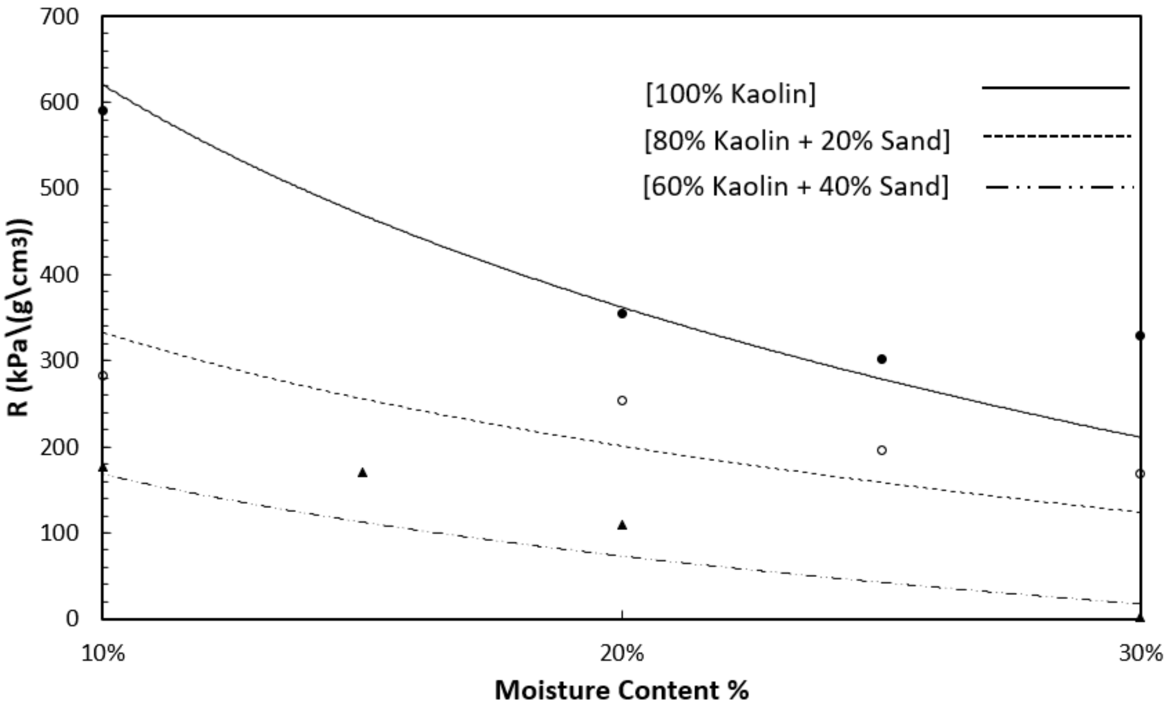

Figure 4.19 Rate of adhesion change for the three soil compositions.

4.3.3 Effect of mineralogy on soil adhesion

Soil composition is one of the factors that controls soil adhesion. The percentage of sand content in clay plays a vital role in soil adhesion. Pure fine-grained soil has a large surface area which produces a large contact area with the solid interface surface, and consequently, high adhesion is expected. As sand content increases, the surface area of the soil and the interface contact area decrease and hence interface adhesion drops. Figures 4.20 and 4.21 show the influence of changing sand content on soil adhesion at different compaction energy conditions and water contents. Soil adhesion decreases as sand content increases.

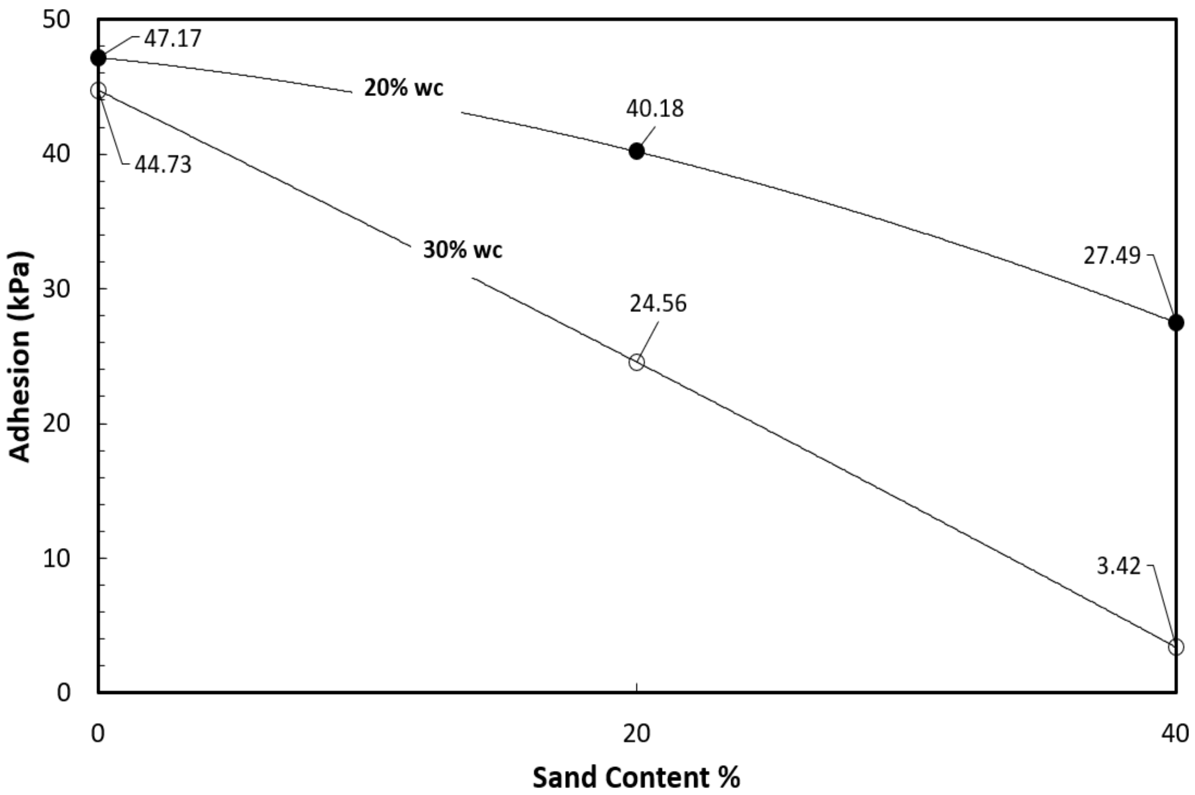

Figure 4.20 Effect of sand content on soil adhesion at standard compaction (25 BL).

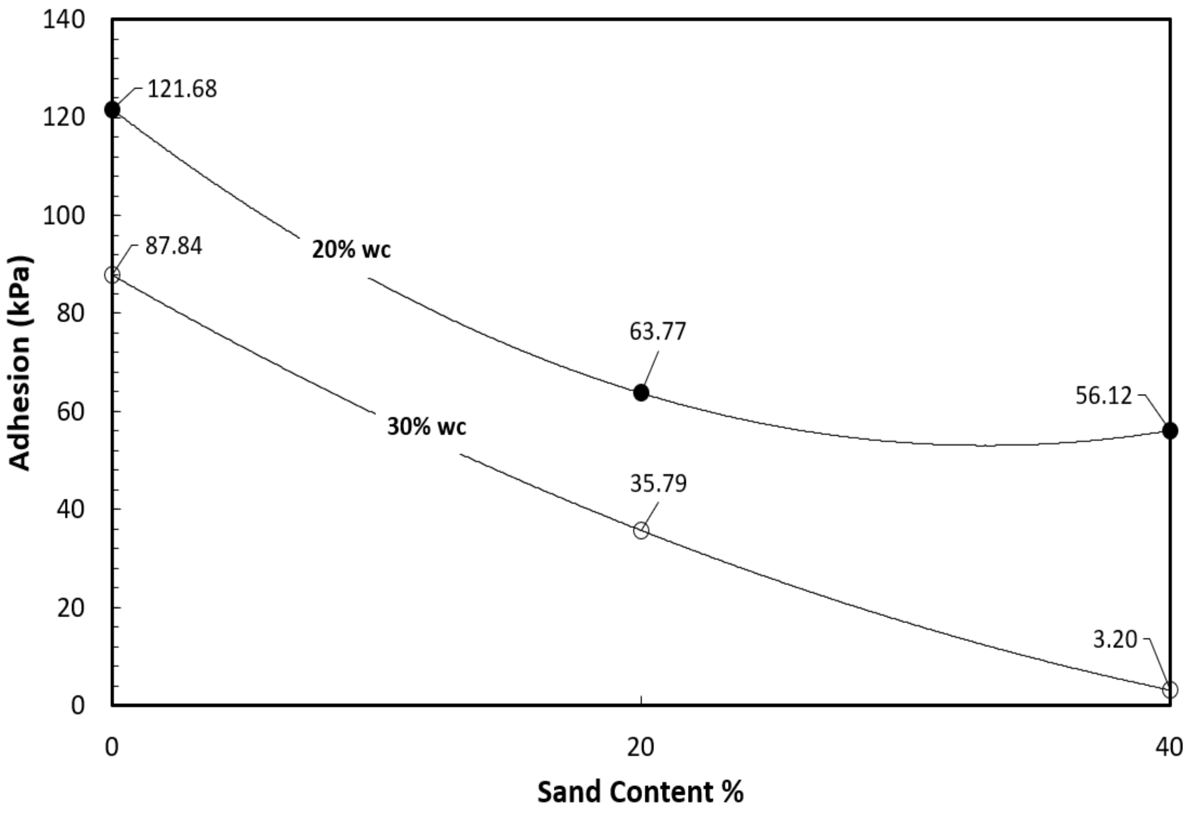

Figure 4.21 Effect of sand content on soil adhesion at maximum compaction (55 BL).

4.4 Conclusion

Shear adhesion is significantly influenced by moisture content, dry density and sand content. For the tested soils in this study, as moisture content increases and soil suction decreases, soil adhesion decreases. However, each soil type goes through different stages of adhesion behaviour as the moisture content changes under the compaction process.

Generally, as dry density increases, soil adhesion increases. However, the maximum and minimum dry densities control the possible adhesion range that can be obtained for each soil type. For kaolin, the rate of adhesion change as dry density changes is larger than that in sandy kaolin. The test results in this study show that the rate of adhesion change per dry density change is a function of moisture content and sand content. This rate decreases as the moisture and sand contents decrease.

Sand content also has a strong impact on soil adhesion. For the same moisture content at the dry side, soil adhesion decreases by adding sand. The existence of sand in kaolin reduces the specific surface area, which in turn, leads to a decrease in soil adhesion. In the case of 40% sand, adhesion is higher at low moisture content instead of reducing, which can be explained in light of the possible interlocking between the sand and the mould surface.

CHAPTER 5:
Conclusion and Recommendations

5.1 Background

Soil adhesion is the adherence of soil particles to the surface of materials. Soil adhesion occurs when it is stronger than soil cohesion. The interfacial adhesion of soil to materials depends on the properties of the soil and materials and is influenced by the testing and environment conditions. Retaining walls, pile foundations, tunnelling boring and agricultural harvesting are examples of the applications of interfacial soil adhesion. Soil adhesion causes issues of stickiness and clogging to the equipment used in the field, which consumes higher energy and affects their work quality.

Several studies have used different methods and devices to investigate the adhesion of various types of soils to steel, rubber and concrete. The methods used to measure soil adhesion included the rotating plate and pull-out load. Several studies in the literature have highlighted the influence of soil type on soil adhesion to continuum surfaces. The adhesion of montmorillonite is larger than kaolinite due to the differences in their physical and chemical properties, such as SSA and CEC. Moreover, soil adhesion is also controlled by the soil moisture content and dry density.

5.2 Experimental program

This thesis investigated the effect of sand content, moisture content and dry density on soil adhesion. Hence, experiments were conducted on 90 samples of kaolin and sand-kaolin mixtures under different conditions of sand content, moisture content and compaction energy. The sand content in the mixtures were 0%, 20% and 40%. The moisture content varied from 10% to 50%, and the compaction energy ranged from 15 blows to 55 blows. This variation in testing conditions assists the investigation of interfacial soil adhesion. A simple novel method was developed to measure the tangential interfacial adhesion between the soil and the internal surface of the brass compaction mould. The soil samples were compacted in the standard modified compaction mould. The LLOYD compression loading machine was used to extrude the compacted specimen and test the shear adhesion at the interface of soil and the inner wall of the mould. The test equipment and procedure suggested in this study does not require any special setup, and it is simple enough to be conducted in conventional geotechnical labs.

5.3 Conclusion

The research revealed that the adhesion of the tested soil is influenced by the moisture content, sand content and dry density. The effects of these parameters on soil adhesion can be summarised as follows:

1- Soil adhesion decreases as moisture content increases and soil suction decreases.

2- When the soil is subjected to constant compaction energy, the soil adhesion-moisture relationship passes through four stages which are mainly controlled by the rate of suction and dry density changes as the moisture content increases.

3- Soil adhesion increases as dry density increases as it increases the contact area between the soil and the continuum surface.

4- Soil adhesion decreases as sand content increases. This behaviour can be attributed to the decrease in the contact surface area as the sand content increases. However, at low water content (high matric suction) increasing the sand content could lead to higher adhesion due to the possible interlocking between the sand and the mould surface.

5- The rate of adhesion change per dry density change is a function of moisture content and sand content. This rate decreases as the moisture and sand content decrease.

5.4 Recommendations for Future Research Directions

There are several factors that are expected to affect the behaviour of interfacial soil adhesion which have not been covered in this research. It is suggested that these factors are considered in future studies. These factors are as follows:

1. Water content salinity
2. Mould material
3. Surface roughness
4. Temperature
5. Loading condition (static & dynamic)
6. Soil fabric
7. Shape of sand particles
8. Plasticity of clay
9. Investigating the effect of the possible interlocking between the sand and the mould surface roughness on adhesion.

Also, it is suggested for the future studies to consider the following:

1. Using bentonite instead of kaolin as it is considered as a reactive clay.
2. Using concrete material instead of metal.

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