Residual shear strength of clay-structure interfaces

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Abstract

The interface between structures and soils is a critical problem in geotechnical engineering. Understanding the shear strength of soil-structure interfaces is important in determining wall or shaft friction for retaining walls and piles, anchor rods, deep foundations, reinforced earth, and buried pipelines. This study deals with laboratory tests on six different clays, three Algerian clays namely: Kaolin1, Kaolin2, and Kaolin3. Three British clays namely : Keuper marl, London clay, and Lias clay. The testing procedures included modified direct shear tests. Each clay was sheared alone, under normally consolidated drained conditions, and against both Sandstone rock and glass. These tests defined the minimum residual strength obtained in each case and provided a basis for a comparison with other published research. It is demonstrated that the residual strength depends mainly on the interface material and its roughness, the properties of the soil, and the magnitude of the clay fraction. The minimum value of residual strength was obtained with the clay sheared against glass. It is concluded that the shear-displacement behaviour of clay-structure interface is similar to that of soil-onsoil.

Keywords: Residual shear strength, laboratory tests, modified shear box apparatus, soil-structure interfaces.

1. Introduction

One of the most difficult problems encountered in geotechnical engineering and construction is how to ensure stability of the slopes of cuttings and retaining walls, and consequently how to assess the limiting strength of soil. The residual shear strength is mobilized after the application of large shear displacements in drained conditions. Its practical significance to slope stability was first recognized by Skempton [1], who proposed the concept of residual strength to long-term slope stability analysis. Therefore, if previous large movements have occurred in the field leading to the formation of shear planes, knowledge of the residual strength will be required for design purposes. The drained residual shear strength of cohesive soils is a crucial parameter in evaluating the stability of pre-existing slip surfaces in new and existing slopes and design of remedial measures Stark & Eid [2].

The ultimate shearing resistance at the interface between soils and solid material is relevant to the stability of friction piles, as shown schematically in figure1. retaining walls. anchor rods, earth reinforcement, submarine pipelines, offshore gravity structures and geomembranes. It is generally different from the residual strength of the soil itself, and depends on the interface material and its roughness as well as on the properties of the soil, the grain size distribution and shape of the soil particles, the magnitude of the normal stress and the rate of shear displacement Lemos & Vaughan [3].



Figure 1. Influence of soil-pile friction on pile capacity.

Most of the research work on soil-interface shear behaviour reported in the literature has been done on sands. Previous studies dealing with the shear resistance of sand sliding on an interface is dependent on the roughness of the contact surface with respect to the size of the sand, sand type, normal stress, density of the sand and rate of displacement. Sand grains tend to slide on very smooth surfaces, giving skin friction angles as low as 10° Yoshimi and Kishida[4], Uesugi et al. [5]. Most of these investigations were carried out with different experimental apparatus such as: direct shear tests have been used to study the behaviour of soil-structure interfaces. Several factors such as structural material, soil properties, and surface roughness have been investigated to better understand their effects on the interface characteristics (Kulhaway and Peterson [6]). Yoshimi and Kishida [4] utilized a ring torsion apparatus for interface testing and observed sand deformation by using x-ray photography. Yin et al.[7] conducted a large shear test to observe the distribution of relative displacement along the interface. Frost et al.[8] studied the evolution of the structure of sand adjacent to the geomembrane, and found that it was directly influenced by the surface roughness.

Paikowsky et al.[9] developed a dual interface testing apparatus that allowed measurement of friction distribution along the interface. Using normalized roughness \mathbf{R}_n and roughness angle $\boldsymbol{\alpha}$, the interface was categorized into three zones: smooth, intermediate, and rough. As pointed out by Boulon [10], the frictional behaviour between sands and solid surfaces is controlled mainly by the complex phenomena that develop within a very thin layer of soil (interface) close to the contact area. This layer of soil can be considered as a zone of intense localisation of shear strains Cichy et al.[11], and the surrounding soil can be thought of as a restraining elastic medium.

Xue et al.[12] have studied the sandstone-concrete joints by using a large direct shear machine (with sample size up to 600 mm in length) under a range of constant normal stiffness and initial normal stress conditions. They found that significant wear of the sandstone surface occurs during shear displacement, and this wear has a significant affect on the behaviour of the joints. Bandis et al. [13] showed that the characteristics of joint surfaces, especially the hardness and roughness of such surfaces, have a major influence on the shear strength of joints. A number of studies have shown that the surface topography is important in the behaviour of soilstructure interfaces [14], [15]. The soil-interface shearing resistance is normally slightly less than the strength of the soil alone, and tends to decrease with decreasing surface roughness [16].

It is worth noticing that most of the previous investigations have studied the interface shear

between sands and solid surfaces. However, the amount of data on the interface shear between clays and solid surfaces is significantly smaller.

2. Experimental Program and Testing Procedures

This study has been carried out by using a modified shearbox apparatus, designed and built in the laboratory, which allows the test specimen to be sheared continuously to displacements large enough to establish residual conditions. The movement of the box and the shearing force developed are recorded automatically from transducers by using data logger systems. The work compares the shear strength of soil interfaces (Sandstone rock and glass) with the same soil when sheared alone.

2.1 Description of the clays used

2.1.1 London clay

The London clay used in this investigation is obtained from a site in Essex (U.K). Block samples were taken from the base of a trench at depths of between 2 and 3 meters, and consisted of a brown, firm clay. The soil classification and properties of London clay are given in Table 1 and Table 2. The clay mineralogy of London clay is dominated by Smectite, Illite, Mica, and Chlorite (see Table 3).

2.1.2 Lias clay

The block samples of blue-grey Lias clay is taken from a limestone quarry near Southam in southern Warwickshire (U.K). The blue grey deposit is very hard, and extreme diffulty has been encountered in preparing satisfactory undisturbed samples for testing due to the tendency for the material to "open" along bedding planes. It consists mainly of clays and shales with occasional bands of limestone and ironstone. Block samples are taken from depths of between 12 and 15 meters below ground level. The soil classification and properties of this Lias clay are given in table 1 and Table 2. The clay mineralogy consists of illite, Mica, kaolinite and Chlorite, the most dominant being Illite and Mica (see table 3).

2.1.3 Keuper marl

The Keuper Marl is a heavily over-consolidated deposit breaking along joints and fissure-planes with a stacky fracture. The keuper marl used in this study is originally obtained in powdered from a local Supplier. The soil classification and properties are given in Table 1 and Table2. The clay mineralogy compositions using X-ray diffraction shows that the keuper marl used in this study has Chlorite as the dominant mineral with traces of Illite and Mica (see Table 3).

2.1.4 Kaolin1, kaolin2, and kaolin3

These three kaolin samples are obtained from an area which is situated in the east of Algeria, North Africa. These materials are used generally for the manufacture of pottery and are removed from a kaolin quarry. Kaolin1 and kaolin2 are similar, both being white in colour, soft and smooth. However Kaolin3 is between blue and black in colour, is hard and it looks as though. The soil classification and properties are given in Table 1 and Table2.

The clay mineralogy of all the Algerian clays are dominated by kaolinite with few traces of Illite and Mica (see table 3). The standard soil classification tests are carried out in accordance with B.S. The pipette method being used to determine the particle size distribution. Figure 2 and figure 3 show the particle size distribution for Algerian and British clays.

	LL (%)	PL (%)	PI (%)	A _c
AC1	104	48	56	0.98
AC2	86	49	37	0.70
AC3	57	34	23	0.53
LonC	87	33	54	0.98
LiaC	45	24	21	0.42
KM	41	22	19	0.48

Table 1. Properties of Clays used in this study

 Table 2. Grain size distribution (According to British Standard)

	Sand (%)	Coarse Silt (%)	Medium Silt (%)	Fine Silt (%)	Clay (%)
AC1	2	9	11	21	57
AC2	7	2	18	20	53
AC3	12	26	10	9	43
LonC	4	15	4	22	55
LiaC	1	17	8	24	50
KM	10	16	12	23	39

Table 3. Clay Mineralogy Composition

using X-ray diffraction

	Mineralogy Composition using in dominant order
AC1	Kaolinite (ordered layers) ; Illite/Mica (very little)
AC2	Kaolinite (better ordered layers) ; Illite/Mica (very little)
AC3	Kaolinite (poorly ordered layers) Illite/Mica (more in comparison to Kaolin 1 and kaolin 2)
LonC	Smectite, Illite/Mica, and Chlorite
LiaC	Illite/Mica, Kaolinite, and Chlorite
KM	Chlorite and Illite/Mica



Figure. 2. Particle size distribution for Algerian clays.



Clay	F.	М.	С.	F.	M.	C.
	Silt		Sand			

Figure3. Particle size distribution for British clays.



Figure 4. Plasticity chart showing results of Atterberg limits on Algerian and British clays

As shown in figure 4, the Algerian clays fall into the MH (high-plasticity silt) group. However, Lias clay and Keuper marl fall into CL (low-plasticity clay) group, and London clay falls into CH (high-plasticity clay) group.

3. Description of the interfaces used

Two interfaces are used: glass interface and sandstone rock interface of $100 \times 100 \times 5$ mm dimension each were prepared by cutting a piece from both sandstone rock and glass into the required size by using a special cutter as shown in figure 5.



Figure 5. Interfaces used in this study

Sandstone is a sedimentary rock composed of small grains cemented by siliceous, felspathic, or calcareous cementing material. The durability of rock depends on the cementing material. Sandstone is often formed in layers and has varied applications as building stones. This coarse-grained sedimentary rock is formed by the consolidation and aggregation of sand and held together by a natural cement, such as silica. It is an extremely hard and tough material and consists of consolidated masses of sand

deposited by moving water or by wind. Some of the sandstone are so homogeneous and soft that they are capable of receiving most elaborate carving and filigree work. The color of the rock is largely determined by the cementing material - iron oxides produces red or reddish-brown sandstone, and the other materials produce sandstone in white, gravish or vellowish sandstone. The chemical constitution of sandstone is the same as that of sand, the rock is thus composed essentially of quartz. The natural cementing material that binds the sand together as rock is usually composed of silica, calcium carbonate, or iron oxide. Chemically sandstone is very resistant Mono-Mineralic rock, with silica as the principal. The percentage of each constituents is as follows :

SiO2 93-94% ; Iron (Fe2O3) 1.5%-1.6% Alumina (Al2O3) 1.4 to 1.5% ; Soda (Na2O) and Potash (Kro) 1.0% to 1.2% Lime (CaO) 0.8% to 0.9% ; Magnesia (MgO) 0.2 to 0.25% ; Loss On Ignition (LOI) 1.0% to 1.2%

Sandstone physical properties

The physical properties of sandstone includes following :

Color: The colour varies from red, green, yellow, gray and white. The variation is result of the binding material and its percentage constituent. *Water Absorption:* The capacity of water absorption

is not more than 1.0%

Hardness: Lies between 6 to 7 on Moh's Scale Density 2.32 to 2.42 Kg/m³

Porosity: The porosity varies from low to very low. *Compressive Strength:* Varies from 365 to 460 Kg/m²

4. Modified shear box test

The need for particular laboratory test techniques, such as those for achieving large strains necessary to measure the residual shear strength, has become apparent. In order to save technician time and reduce the difficulties of interpretation by obtaining consistent test results which is a vital step. The research work has been carried out by using a modified shear box apparatus, designed and built in the laboratory, which allows the test specimen to be sheared continuously to displacements large enough to establish residual conditions. The normal stresses were applied by using an electro-pneumatic converter controls the pressure of the air supply, the output pressure being proportional to the direct current supplied. The converter gives a pressure output of 0-690 kPa. Figure 6 shows the electropneumatic converter which controls the applied normal stresses.



Figure 6. Shows the electro-pneumatic converter which controls the applied normal stresses.

In this apparatus, the gears have removed and the motor has been replaced by a stepper motor controlled directly from the data logger by fixing the number of pulses necessary to drive the motor to the required distance (see figure 7).



Figure 7. Direct connection between the motor and the drive unit.

The rate of shear for the modified shear box was fixed to 0.015873 mm/min, a value that was found by preliminary tests to ensure drained conditions throughout the test.

5. Interface tests

An extensive program of tests was conducted to examine the peak and residual strength, and to study the shear-displacement behaviour of six clays when sheared alone and against two plane interfaces. Every clay is sheared against sandstone rock and against glass. The shearbox is assembled in the testing machine, with the sandstone rock in the bottom half and the clay placed in the top half of the box. A porous stone is placed above the specimen and below the sandstone rock and gentle pressure on the upper porous stone forced the specimen into the correct position for testing. The loading head is then assembled. The normal stress is applied throughout the test by using the micro-computer and the sample is sheared with rate of shear fixed to 0.015873 mm/min for both forward and backward shear cycles. For the tests of clay sheared against glass, the procedure of testing is the same, except that smooth plate glass instead of sandstone rock is located in the bottom half of the box. After five complete cycles of shear, the drive is dismantled and the surrounding water in the water bath is drained. The normal stress is removed automatically throughout the computer, the shearbox is dissembled and excess moisture removed prior to studying the shear surface.

A primary purpose of this study is to investigate the residual strength of the interfaces and their relative residual strength compared to the clay sheared alone. For this reason tests are carried out using the same rate of shear and the same normal stresses. These tests have an application in the study of the intercalation between hard rock layers, where the problems of zones of weakness in rock masses is significant. Such a problem can occur in natural and artificial slopes, open cuts and excavations, foundations and abutments of dams. and underground openings.

6. Surface roughness

The importance of the degree of surface roughness at interface behaviour and soil-structure interaction response, have been noted by many investigators (e.g., [17], [18], [15].

The surface roughness can be measured with a Taylor-Hobson Talysurf stylus profilometer. A schematic of the profilometer is shown in figure 8. As the figure illustrates, the profilometer comes equipped with a diamond stylus tip that traverses the surface to be characterized. Transducers in the profilometer help record the vertical and horizontal coordinates of the stylus tip. Therefore, the raw surface profile data consists of a series of discrete coordinate pairs (x, z) that can be post-processed and analyzed to obtain the surface topography characterization of the material investigated [15].



Figure 8. Stylus profilometer sketch [21].



Figure 9. Graphical representation of roughness parameters Rt, Sm, and Ra.

Surface topography was quantified by three commonly used roughness parameters: the maximum peak-to-valley height (Rt), the average mean line spacing (Sm), and the arithmetic average roughness (Ra). Sm is twice the mean distance between locations at which the profiles cross the centerline drawn through the centroid of the profile. Ra is the arithmetic average value of the profile departure from the mean line along the profile length. These three roughness parameters are illustrated in figure 9. More detailed discussion of these parameters is given in International Organization for Standardization (ISO) Standard 4287 (ISO 1997)[19].

The surface roughness values presented by the arithmetic average roughness (Ra) of some interface material are summarized in table 4.

 Table 4. Surface roughness values of some interface material.

Interface material type	Arithmetic average roughness (Ra) ; (μm)
Glass (very smooth)	0.005
Concrete	28.0
Steel	5.7
Sand blasted with coarse	7.0
sand	
Sandstone rock	10.0

Note: 1 (μ m) = 0.001 mm

7. Discussion of Test results

All the soils' behaviour is discussed in terms of effective stress. The results of tests performed thus give more understanding to the problems of structures which are subjected to large relative displacements, and the effect of other phenomena such as the strength of shear zones on the sides of driven piles. Tomlinson [20], in his significant contribution to the understanding of the behaviour of piles in clay over the years, agreed that it was important to focus on the behaviour of a thin laver of soil adjacent to the pile. An attempt has also been made to obtain a more complete understanding of the difference which exists between the clavs sheared alone and the clav-structure interfaces. The results of all these investigations are discussed below.

7.1 Discussion on the results of Interface tests

The purpose of this section is to report the tests in order to investigate the shear strength of interfaces.

The stress-displacement curves (kaolin1 on kaolin1) for clay sheared alone are shown in Figure 10(a) for forward cycles and figure 10(b) for backward cycles.



Figure 10(a). Stress-displacement relationship for Ac1/AC1 Using Modfied Shearbox at 0.015873 mm/min.



Figure 10(b). Stress-displacement relationship for Ac1/AC1 Using Modfied Shearbox at 0.015873 mm/min

The stress-displacement curves for the interface (kaolin1 on sandstone Rock) are shown in Figure 11(a) for forward cycles and figure 11(b) for backward cycles.



Figure 11(a). Stress-displacement relationship for Ac1/Rock Using Modfied Shearbox at 0.015873 mm/min.



Figure 11(b). Stress-displacement relationship for Ac1/Rock Using Modfied Shearbox at 0.015873 mm/min.

The stress-displacement curves for the interface (kaolin1 on Glass) are shown in Figure 12(a) for forward cycles and figure 12(b) for backward cycles.



Figure 12(a). Stress-displacement relationship for Ac1/Glass Using Modfied Shearbox at 0.015873 mm/min.



Figure 12(b). Stress-displacement relationship for Ac1/Glass Using Modfied Shearbox at 0.015873 mm/min.

It is worth noticing that the curves for interface tests (Figures 11 and Figure 12) are similar except that the drop in strength for soil sheared against either sandstone rock or glass occurs quickly after the peak strength is reached. This is explained by the plane surface facilitating the reorientation of clay particles and the destruction of the bond between particles during shearing being aligned in the shear zone quickly.

The peak shear strength is reached at about 0.1 mm for both clay sheared against sandstone rock and

clay sheared against glass although the roughness is not the same. This can be explained by the particles have not been displaced a sufficient distances relative to their initial contact positions. Lupini et al. .[21] presented an extensive study on the residual strength of cohesive soils as measured in the ring shear apparatus. They found that residual strength measured at slow drained displacement rates resulted from three types of shearing mechanism.

In the first mechanism large strain involves rotation of the rotund particles, as in granular soils, and particle orientation has a negligible effect. This mode of deformation is termed turbulent shear. If a high proportion of clay particles is present, a continuous orientation shear surface can form between any rotund particles. This mode of deformation is termed sliding shear. At intermediate proportions of clay particles, oriented shear surfaces can partly form, but are continuously disrupted by the rotund particles. This mode of shear is termed transitional shear. Turbulent residual shear has thus been defined as the state of residual shear at constant volume for which no particle orientation occurs. In this case soils that shear at residual conditions exhibit typically high residual strengths with ϕ'_r in excess of 25 degrees.

The results reported herein indicate that all the residual shear strengths are under 25 degrees, which in turn indicates that the samples exhibit either sliding shear mode or transitional shear mode. It can thus be stated that particle orientation is involved in all of the shear mechanisms and this will lead to a residual state being reached at large displacements. The sliding shear mode is characterised by a shear surface that is formed by strongly oriented clay particles and usually has a low residual friction angle (typically in the range from 5 to 12 degrees).

The highest residual strength angle, ϕ'_r for Kaolin3 is typically 20.8 degrees, when sheared in the modified shearbox. An explanation of this high value could be attributed to the mineralogy of Kaolin3, which is entirely dominated by kaolinites. This was shown by Lupini et al.[21] who tested soils of different mineralogies, and found that Montmorillonite soils had the lowest residual friction angle, and Illite or kaolinite soils the highest. With regard to this the results indicated that all the three Algerian clays contained predominantly

kaolinite, and the residual friction angles are 11.8, 17.6, and 20.8 degrees for Kaolin1, Kaolin2, and Kaolin3 respectively. Despite the first clay having a slightly lower value in comparison with the other two clays, such a relationship is not always true. The Lias clay with Illite constituting the dominant mineral, gave $\phi_r = 12.1$ degrees. From which it can be seen in fact that there is only a relatively small difference, between this value and the value of Kaolin1. In this study, Kaolinitic soils gave results ranging between 11.8 and 20.8 degrees. Despite keuper marl not being dominated by either Illite or by kaolinite, it gave a high residual strength angle of 20.4 degrees. As far as the clay fraction is concerned, keuper marl is mainly dominated by silt particles which are not platelets, as reported by Mitchell [22] related residual strength to particle shape. They found that low residual friction angles are associated with platy particles, and that subangular and needle-shaped particles gave high residual friction angles. Regarding these findings, and that because silt contains many rounded particles, the mechanism of failure involved particle rolling and translation, rather than direct sliding, this being prevented by interlocking of the particles. It is therefore, possible that during shear, the continuous oriented planes are interrupted by the silt particles, such that the silt particles gave high residual friction angles. In contrast, London clay has the lowest residual strength angle of $\phi_r = 8.2$ degrees, for which a possible explanation could be related to the high clay fraction which is 55%. The low residual friction angle is associated therefore, with good oriented bands of high clay fraction, Preferentially orientated. This produced a low residual strength during shear. As mentioned earlier, concerning the low friction angles (typically in the range from 5 to 12 degrees) it seems that only kaolin1, London clay, and lias clay values lie in this stage.

The drop in strength post-peak is found to occur quicker with the glass interface than with the rock interface. The relatively quick drop in strength with the glass interface can be explained by the smoothness of the surface parallel to the plane and hence to each other. Evidence that the formation of orientation domains begins at relatively small strains was achieved by Goldstein et al.[23]. There is also such evidence for the presence of continuous bands of almost perfectly orientated particles in clays subjected to large strains, both in the

laboratory Astbury[24] and field in the Skempton[1]. It is clear from this study that the glass acts solely as an interface for the reorientation of clav particles and that the smoother the surface. the more rapid the reduction in strength and the lower the measured residual angle. Another purpose for using the glass interface is to find a relationship between the results from the modified shearbox and the Bromhead ring shear, with the aim of producing comparable values so that the commonly available standard shearbox can be used instead of the much rarer ring shear for residual strength testing.

Kanji and Wolle [25]tested soils against hard polished rock. They found that the peak shear strength τ_{max} was lower and occurred at small displacement, and also that there is a rapid drop in strength after the peak strength had passed. They explained this drop by stating that the hard polished surfaces encourage the development of residual strength at small shear displacement. In this study, it was found that the clay sheared against glass gave the lowest values of peak and residual strength, for all six clays, compared with rock. The difference between the strengths for both sandstone rock and glass interface tests given below in Table 5.

 Table 5. The difference between strengths

 of sandstone rock and glass interface tests.

Clay	$\Delta \phi'_r = \phi'_r$ (Clay-Rock)	$\Delta \phi'_{P} = \phi'_{P}$ (Clay-Rock)
	- ϕ'_{a} (Clay-Glass)	- ϕ'_P (Clay-Glass)
	(Degrees)	(Degrees)
AC1	1.6	3.4
AC2	2.6	1.5
AC3	3.3	2.1
LonC	1.6	2.9
LiaC	1.8	1.7
KM	4.8	5.1

The tests have thus yielded the following ranges.

1.6°
$$\leq \phi'_r$$
 (Clay-Rock) - ϕ'_r (Clay-Glass) $\leq 4.8°$
1.5° $\leq \phi'_P$ (Clay-Rock) - ϕ'_P (Clay-Glass) $\leq 5.1°$

Since the development of shears in clay is accompanied by particle orientation, the difference between the two interfaces could therefore be attributed to the fact that the smooth area of glass permits the clay particles to be more strongly orientated in the direction of movement than the sandstone rock interface. It is worth noticing from these differences that the smooth interface, against which the particles have attained their maximum degree of orientation, must possess the minimum possible resistance to shear, which is defined as the residual strength of the clay. From this examination it is reasonable to suppose that the interface leads to the ready destruction of the cohesion and that there is a strong orientation of clay particles parallel to the surface of shear.

Furthermore, clays tested against a smooth interface (rock or glass) show lower strength values. This reduction in strength could be explained largely by the orientation of particles along the shear zone, due to the smoothness of the plane surface of the interfaces. The strength values obtained by the Bromhead ring shear for clay-on-clay are found to lie in between the strength values of clays tested against the smooth plane surface (rock or glass), with the lowest values obtained with the clay sheared against glass. This correlation shows definitely the great role played by the reorientation of the particles during shear. The absolute residual strength values as a percentage of the residual Bromhead ring shear values are given below in table6.

Table 6. Residual strengths measured in the MSBas a percentage of Bromhead ring shear values.

Clay	AC1-AC1	AC1-Rock	Clay-Glass
	%	%	%
AC1	139	107	88
AC2	134	106	87
AC3	130	114	95
LonC	121	102	85
LiaC	133	112	92
KM	123	112	85

It is clear from table 6 that the range for clay-clay is higher than the two residual interface tests, which is between 121% - 139%, whereas for rock and glass, the results lie between 106% - 114% and 85% - 95% respectively.

7.2 Residual shear envelope

Figure 13 presents the drained residual strength failure envelope for the six clays tested during this study. It can be seen that the drained residual strength envelope is nonlinear. This nonlinearity is more significant for British clays especially for effective normal stress between 100 kPa and 200 kPa. This nonlinear behaviour may be caused by the presence of weak partly weathered particles that

disaggregate upon shearing especially at low normal stress values. According to the plasticity chart, the British clays classified as CL-CH groups. The nonlinearity of the residual failure envelope for London clay agreed with the findings of Stark and Eid [26] that the nonlinearity of the residual failure envelope is significant for cohesive soils with a liquid limit between 60% and 220% and a clay fraction greater than 50% where the London clay (liquid limit is 87% and clay fraction is 55%) fulfil the condition suggested by stark and Eid [26]. However, Keuper marl shows nonlinear residual failure envelope although have liquid limit less than 60% and clay fraction of 39% and is classifies as CL group.

It is worth noticing that the Algerian clays showed a linear failure envelope and they can be fitted into the linear regression with R^2 equal to 0.99. although these clays are classified as MH group. London clay and Keuper marl can be fitted into the linear regression with R^2 equal to 0.97 and 0.98 respectively.



Figure 13. Drained residual shear envelope for all clays (by using modified shearbox tests)



Figure 14. Drained residual shear envelope for clay against sandstone rock interface.



Figure 15. Drained residual shear envelope for clay against sandstone rock interface.

Figure 14 and figure 15 present the drained residual failure envelopes for the six clays sheared against the sandstone rock and against glass respectively. It is worth noticing that the drained residual failure envelopes for clavs sheared against interfaces(sandstone rock and glass) gave less nonlinearity compared to clay-on-clay. Therefore, it may be concluded that the nonlinearity of the residual failure envelope for soil-on-soil is more greater and significant than the clays sheared against interfaces (sandstone rock and glass). The degree of the nonlinearity of the drained residual shear envelope is minimized especially for the clayglass interface which is clearly observed at figure 15. It seems that the degree of nonlinearity is strongly dependent on the surface roughness.

4. Conclusions

The following conclusions have been drawn from this study :

- The shear failure envelope for the studied Clay-structure interfaces obeys the Mohr-Coulomb failure criterion.
- It was found that the mode of shear mechanism in general for clays/structures interfaces was changed by the structure surface roughness.
- For the studied interfaces, the shear strength of the clay-on-clay is greater than that of the clay-structure interface for similar stress conditions.
- Results that are presented in this study will enhance the understanding of the shear behaviour of clay-structure interface that is crucially important in stability analysis of the interface between soils and solid materials in general.
- From the work reported on the interface tests, it is possible to suggest that if a soil shows a transitional residual mode of behaviour which involves a combination of both turbulent and sliding shear and is sheared against a smooth hard interface (e.g. glass used in this study), the residual conditions can be altered to a sliding shear mode involving a low residual shear strength in comparison to the soil sheared alone. This is demonstrated by values given by kaolin1.
- The interface test is a best method to obtain the residual strength of clay soils, constituting a simple, rapid and economical method. This fact is due to easier clay particle orientation at the vicinity of the contact with the interfaces.
- Although this study is performed on a limited range of interface roughness. It is believed that the interface roughness has a great influence on clay-structure shear behaviour. Further research is needed to provide a better understanding of the

behaviour of the clay-structure interface for a wider range of surface roughness.

Abbreviations

MSB	:	Modified Shear Box
AC1	:	Kaolin 1
AC2	:	Kaolin 2
AC3	:	Kaolin 3
LonC	:	London clay
KM	:	Keuper Marl
LiaC	:	Lias Clay
SSR	:	sandstone rock
GL	:	Glass
CL	:	Low-plasticity clay
СН	:	High-plasticity clay
ML	:	Low-plasticity silt
MH	:	High-plasticity silt
OH	:	High-plasticity organic soil
LL	:	Liquid Limit
PL	:	Plastic Limit
PI	:	Plasticity Index
A _C	:	Activity $A_C = (PI)/CF$
F.	:	Fine
M.	:	Medium
C.	:	Coarse
SSR	:	Sandstone Rock
GL	:	Glass

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