

Experimental Investigation of Frictional Behavior Between Cohesive Soils and Solid Materials Using Direct Shear Apparatus

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Abstract Soil shearing resistance is very important while designing various structures which have direct contact with soil, for example, sheet piles, piles, retaining walls, reinforced earth structures and shallow foundations. Even though designers use empirical values for their design, it is very important to obtain more accurate values for soil–solid materials shearing resistance. In this work, laboratory tests have been carried out to investigate the effect of roughness interface and texture models on friction angle between cohesive soils and steel, as well as abrasive paper material, using direct shear tests. All tests were carried out under consolidated drained shear conditions. The behavior at the soils–solid interface was found to vary according to surface roughness. It also seems that the type of material (steel or paper of abrasive) used does not have a major influence on the shear strength. As far as roughness is concerned, friction behavior is likely to be generally classified into three failure modes,

namely full sliding at the interface, shear failure within the soil, and a mixed behavior where interface sliding and shear deformation of the soil specimen proceed simultaneously. However, for the second mode, the shear strength at the interface soil–rough solid materials steel was found to be lower than the shear strength of the soil, for a soil that is classified as high plasticity clay. Furthermore, it was found that the interfacial shear strength is independent of the texture surface for a given roughness.

Keywords Shearing resistance · Soil–solid interface · Roughness · Surface texture

1 Introduction

Many civil engineering problems involve estimation of stresses transferred along the interface between soils and solid surfaces. While considerable works have been conducted on the interfacial friction between cohesionless soils and solid materials, comparatively few studies are available in the literature on the interfacial resistance between cohesive soils (fine grained soils) and solid surfaces, resulting in fewer studies on the mechanisms involved in interface shear for the latter. The mechanical properties of soil–structure interfaces are significantly affected by two important factors: the interface roughness and loading conditions.

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Earlier soil structure interface research has been undertaken by Potyondy (1961). He studied the friction between different construction materials and soils, postulating that the most important factors affecting the friction are: normal stress level, moisture content, solid material roughness and soil composition. Direct shear tests have then been extensively conducted by other researchers. For instance, Tsubakihara and Kishida (1993) carried out laboratory tests on friction between cohesive soils and mild steel using two types of apparatuses: a simple shear type and a direct shear type. The cohesive soils were normally consolidated Kawasaki clay and four kinds of normally consolidated sand–clay mixtures. They postulated a critical roughness which distinguishes between two modes of shearing. When the surface is smoother than the critical roughness sliding took place at the interface. On the other hand, a shear failure within the clay sample occurs when the roughness exceeds the critical value and the limiting strength value is that of the clay. There was little difference in the maximum friction coefficient between the tests with different mixture ratios of sand. Tsubakihara et al. (1993) tested cohesive soils against mild steel interfaces using the simple shear apparatus. They observed three failure modes: shearing within the soil placed against a rough surface, sliding of the soil along a smooth interface and for clay–sand mixtures, partial sliding in localized areas of the interface contact area. Subba Rao et al. (2000) used a modified direct shear apparatus to study the effects of surface roughness, soil type and overconsolidation ratio on the shear strength at the interface fine grained soils–solid materials. They used three types of soils and five plates of stainless steel (material 1 smooth), mild steel (materials 2 and 3, intermediate roughness) and concrete (materials 4 and 5, high roughness). An empirical correlation has been proposed to determine the angle of interface friction. They also indicated that the ratio of the interfacial friction angle to the angle of internal friction of the soil is independent of the overconsolidation ratio. Chu and Yin (2005) examined the effects of surface roughness on the shear strength of an interface between a cement-grout nail and the surrounding soil. It was observed that both the cohesion and the friction angle at the interface increase with the increase of the surface roughness of the soil-grout interface. Shakir and Zhu (2009) carried out interface tests between compacted clay and concrete by means of interface simple shear apparatus, using samples having the same dry density

with different water content ratios. Two types of concrete interfaces with different surface roughness (relatively smooth and relatively rough) were used. The main objectives of this work were to show the effect of water content, normal stress and rough surface on the shear stress–shear displacement relationship at the clay–concrete interface. They concluded that the interface shear sliding dominates the interface shear displacement behavior for both cases of relatively rough and smooth concrete surface except when the clay water content is greater than 16 % for the case of rough concrete surface where the shear failure occurs in the body of the clay sample.

The object of the present paper is to study the influence of two main factors namely roughness and texture model on frictional behavior between cohesive soils and solid material using a shear box apparatus.

2 Experiment

2.1 Testing Apparatus

The direct shear box was used in this investigation. It presents two main advantages: wide availability and relatively simple test setup and sample preparation procedures. Consequently, it has been the common choice for interface testing in research and practice. Although, the maximum relative displacement that can be attained is limited; hence, the determination of the interface residual strength becomes difficult. In addition, end effects induced by the presence of the rigid walls of the soil container may lead to errors in the test results.

For the present study, a commercially available direct shear device is used. The square contact surface was (60 × 60) mm, while the contact area in the friction test remained constant during a test. The normal stress is applied to the specimen by means of a vertical load hanger which rests on the yoke above the soil specimen. The shear force is measured by means of a transducer fitted with a proving ring. The vertical and horizontal displacements of the soil specimen are also measured using transducers.

2.2 Sample Preparation

Each sample used for this experimental investigation was prepared from slurry by mixing dry soil with

distilled water at the liquid limit. After ensuring a thorough mixing, it is then left to dry until it reaches a water content equivalent to 1.5 times the plastic limit approximately. The inner side surface of the container was lubricated by silicon grease in order to reduce the friction between the edges of the box and the solid materials surface. The soil sample is then inserted into the direct shear box carefully. A sample thickness of 25 mm ± 1 mm is adopted for the soil–soil test and 15 mm ± 1 mm was used for the soil–solid interface test. The procedure adopted satisfies the recommendations of Jardine and Chow (1996). Consolidation is then initiated. Once it is complete, shearing takes place at a rate of shearing of 0.02 mm/min, which was found to ensure full dissipation of excess pore water pressure. All transducers are properly setup. The test is started and readings of horizontal displacement, normal displacement and shear force are recorded. The shear test is stopped after observing a noticeable decrease in the value of shear force or a stabilization of the readings. The normal load is kept constant at a specific value during each test. In all cases, the shear stresses were applied at the end of primary consolidation after application of normal stresses of 109, 150 and 204 kPa respectively.

The soils used in this investigation include four kinds of cohesive soils: two types of kaolin (K1 and K2), clay of Guelma (CG) and a mixture of 50 % K1 and 50 % CG (K1G). Their index properties are presented in Table 1. The grain size distribution curves were determined according to the conventional procedure and are shown in Fig. 1.

As shown in Fig. 2, according to the plasticity chart, K2 and CG fall into CH (clay of high plasticity) group, while K1 and the mixture of 50 % CG and 50 % K1 (K1G) fall into the MH (Silt of high plasticity) group.

Table 1 Index properties of tested soils

Properties	K1	K2	CG	K1G
Liquid limit w_L (%)	73	60	75.5	70.5
Plastic limit w_P (%)	36.7	30	34.2	35.44
Plasticity index IP (%)	36.3	30	41.3	35.06
Clay fraction (% < 2 μm)	6.6	64	44	26.17
Average diameter D_{av} (μm)	17.50	2.06	3.4	11.85
Activity A_c	5.50	0.47	0.94	1.34
Specific gravity G_s	2.60	2.60	2.78	2.60

2.3 Surface Roughness

In this investigation different square plates of mild steel were fabricated. Each plate has a surface area of (128 mm × 128 mm) and is 14 mm thick with a purpose to prepare interfaces of different degrees of roughness and different texture models. In order to design homogeneous interfaces, a combination of two factors has to be taken into consideration, namely surface roughness (i.e. height of asperity) on the one hand and texture model (distribution of asperities) on the other hand. The roughness of each specimen was finished to a specified roughness. The smoothest one (i.e. SI1) was obtained by plane rectification, while the rough ones were obtained by milling. The depth of impression can be adjusted according to the pressures applied to the knurls to obtain different types of roughness.

The following types of interface have been used in this investigation:

- One smooth plate (SI1);
- Three grooved plates (SI2, SI3, and SI4);
- Four plates with abrasive papers (AI1, AI2, AI3, and AI4).

Figure 3 illustrates the topography of used steel interfaces. In Table 2, the roughness characteristics of the four interfaces are presented. For the last type of interfaces, different types of abrasives-papered were stuck to the surface of steel plate.

Many investigators have shown that surface roughness plays a major role in interface behavior (Uesugi and Kishida 1986; Paikowski et al. 1995; Suriyavut pra 2013). To conduct a meaningful examination of the fundamental mechanisms controlling interface shear, it is necessary first to characterize the materials involved. In the present study a method of roughness description which is standard in tribology was adopted, the center line average R_a roughness parameter. The latter is the arithmetical mean of the areas of all profile values of the roughness profile:

$$R_a = 1/Le \int_0^{Le} |y(x)| dx \quad (1)$$

where $y(x)$: height values of the roughness profile; Le : sampling length.

In geotechnical applications, roughness of a surface must be defined in terms of the predominant length scale of soil grains at the interface. In this work, the

Fig. 1 Grain size distribution curves

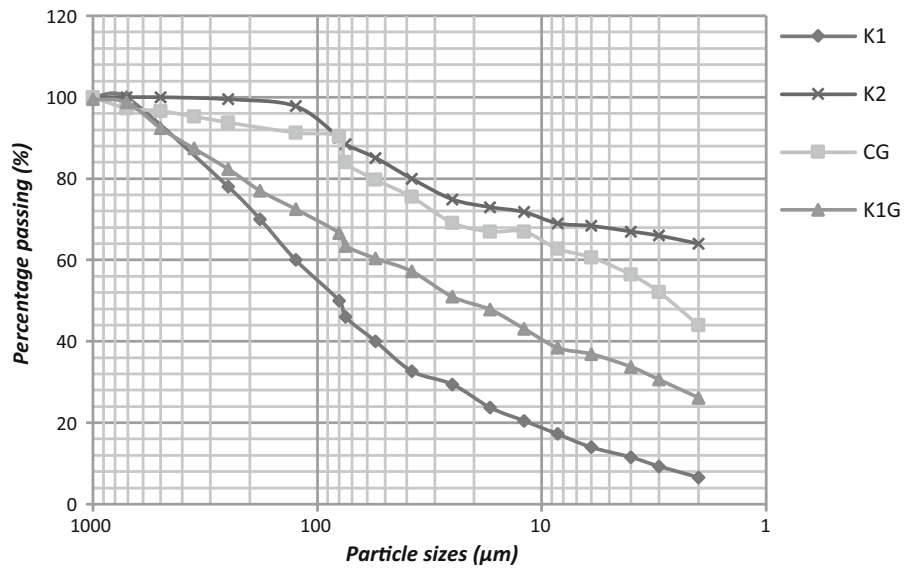


Fig. 2 Plasticity chart showing classification of tested soils

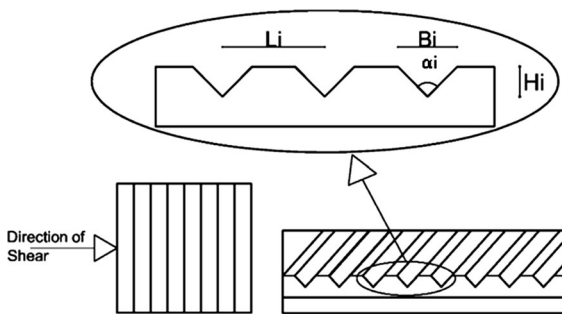
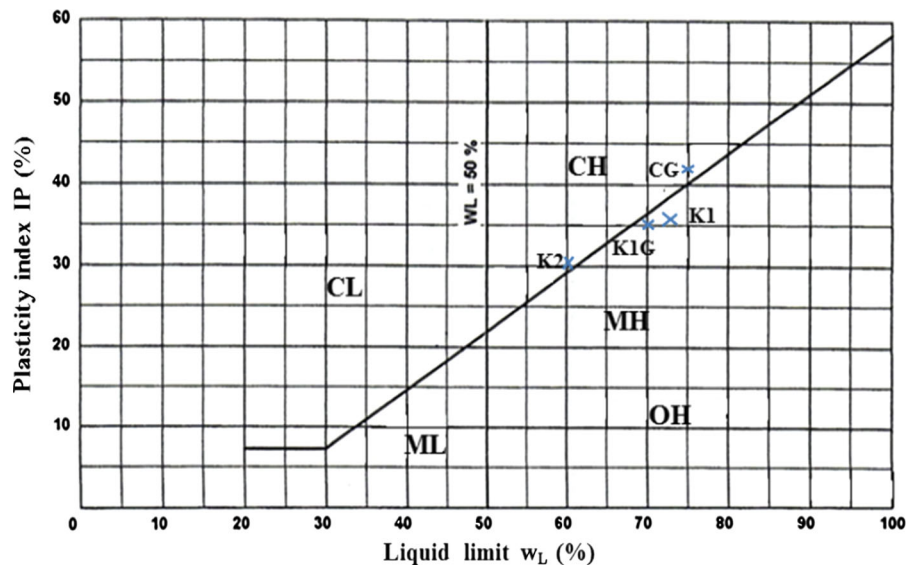


Fig. 3 Topography of grooved steel plates

Table 2 Surface roughness characteristics

Interface	B_i (mm)	H_i (mm)	L_i (mm)	α_i (°)
S11	0	0	0	0
S12	0.16	0.20	2.16	45
S13	0.23	0.20	2.23	60
S14	0.41	0.50	1.41	45

method proposed by Subba Rao et al. (1998) which uses a relative roughness R was adopted. It consists of normalizing R_a with respect to the average diameter of

the soil particles D_{av} . The latter can be obtained from the grain size distribution curve of the tested soils, using an arithmetical scale for the particle size. R is defined as:

$$R = \frac{R_a}{D_{av}} \tag{2}$$

The average diameters of tested soils are given in Table 1. It is noted that the relative roughness R , decreases with increasing D_{av} . The decrease in relative roughness reflects the fact that large particles tend to move more smoothly than small ones when they slide across a surface with the same roughness. The average values of R_a and R obtained are given in Tables 3 and 4 respectively.

Moreover, in order to study the effect of texture model on the shearing resistance at the interface of cohesive soil–solid material, four types of texture have been used. The texture models selected are illustrated in Fig. 4. These textures are characterized by the same roughness, namely $R_a = 5.69 \mu\text{m}$.

3 Results, Analysis and Discussion

3.1 Effect of Roughness

3.1.1 Test Results

The friction shearing at the interface of soil–solid material is often represented by the shearing effective stress τ acting at the soil–solid material interface. Figures 5, 6 and 7 show shear stress–horizontal displacement relationships obtained for K1, CG, and K1G samples sheared against steel and abrasive paper. The results obtained are summarized in Tables 5 and 6. In these tables ϕ is the peak angle of internal friction obtained for soil–soil shearing. For interface shearing δ refers to the peak angle of interface friction. Δ is the average displacement necessary to attain pic conditions.

Table 3 Values of R_a (μm)

Steel interface				Abrasive paper interface			
SI1	SI2	SI3	SI4	AI1	AI2	AI3	AI4
0.21	5.69	21.04	64.94	5.49	5.66	9.44	10.66

Table 4 Values of R

Interface	K1	K2	CG	K1G
SI1	0.012	0.102	0.062	0.018
SI2	0.324	2.762	1.674	0.480
SI3	1.200	10.214	6.188	1.776
SI4	3.702	31.524	19.100	5.480
AI1	0.313	2.665	1.615	0.463
AI2	0.323	2.748	1.665	0.478
AI3	0.538	4.583	2.776	0.797
AI4	0.608	5.175	3.135	0.900

The standard direct shear tests (K1S, CGS and K1GS), where soil–soil shearing takes place, have shown that all materials exhibit a hardening behavior. The curves deduced from tests carried out for soil–soil shearing show the highest shear stresses with no clear peak values. The results obtained for K1 under different normal stresses were analyzed to obtain the required shear strength parameters. Thus, an average internal friction angle value of 25.39° was deduced. This value seems to be in accordance with the results obtained by some authors for different types of kaolin. Smith and Reitsma (2002) showed that typical angles of kaolin clays are located between 20° and 25° . Furthermore, Hammoud (2006) obtained an internal friction angle value for kaolin of 19.3° as a result of ring shear tests. While Tan et al. (2008) using a direct shear box, showed that the internal friction angle for kaolin clay of high plasticity was 30.78° . The development of peak strength is derived primarily from the breakdown of the bond in the soil structure; this develops relatively high strengths over a small displacement. As expected there was no cohesion intercept since the samples tested were normally consolidated.

As far as shearing tests at the interface are concerned, there was no adhesion whatever the magnitude of roughness. When K1 is sheared against steel or abrasive paper, δ values were found to vary between 17.45° and 24.87° , for rough interfaces. The interface angle values are therefore lower than the soil–soil internal friction angle. The horizontal displacements required to reach the peak conditions were found to range between 1.52 mm and 4.51 mm. The peak friction coefficient (τ/σ_n') is about 0.265 for K1 sample in the case of the smoothest surface (i.e. SI1)

Fig. 4 Texture models of used steel interface

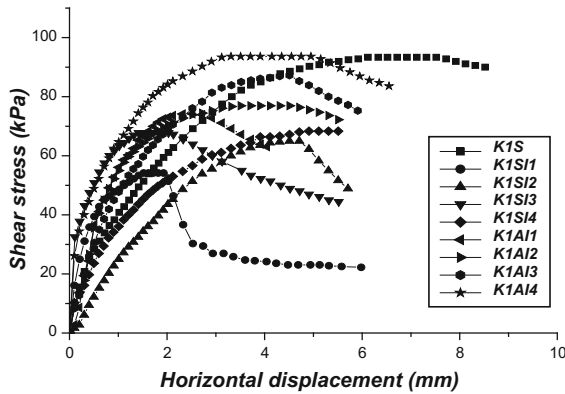
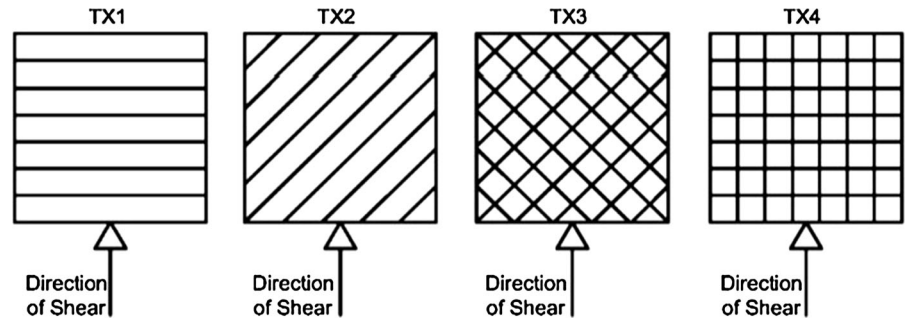


Fig. 5 Typical shear stress-horizontal displacement curves of K1-steel and abrasive paper interfaces at 204 kPa

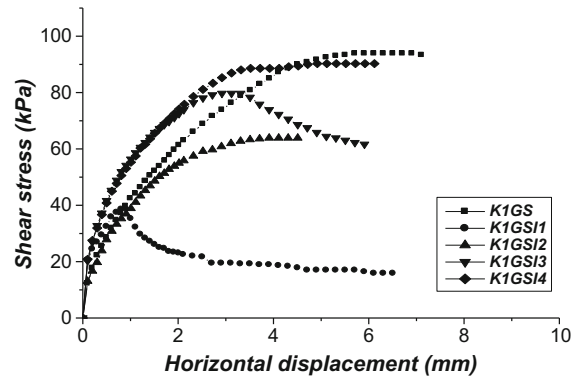


Fig. 7 Typical shear stress-horizontal displacement curves of K1G-steel interfaces at 204 kPa

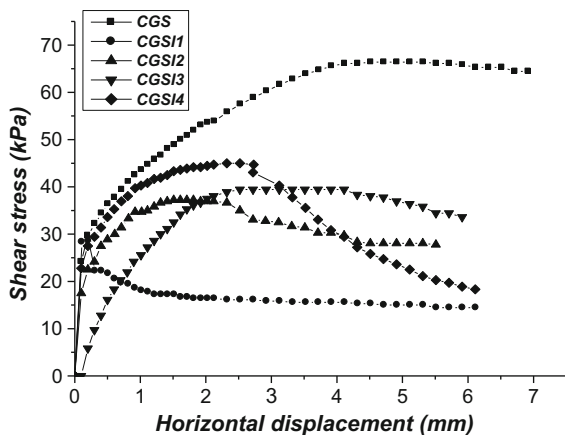


Fig. 6 Typical shear stress-horizontal displacement curves of CG-steel interfaces at 204 kPa

for which $R_a = 0.21 \mu\text{m}$, at a normal effective stress of 204 kPa. It is worth mentioning that Lemos and Vaughan (2000) used direct shear tests on speswhite kaolin, consolidated from slurry to a normal effective stress of 200 kPa and sheared at a rate of 0.0337 mm/

Table 5 Test results on K1, CG and K1G for soil–soil interface

Test	ϕ (°)	Δ (mm)
K1S	25.39	6.12
CGS	18.60	4.51
K1GS	24.56	5.71

min against a mild steel surface with a smooth interface ($R_a = 0.215 \mu\text{m}$) and obtained a peak friction coefficient (τ/σ'_n) of about 0.345. The discrepancy in the friction coefficient values for both kaolin types may be attributed to the fact that the soils tested have different physical properties. The displacement rate is also likely to have an effect. Regarding CG soil, δ values were found to range between 10.21° and 12.43° for rough steel interfaces. It is noted that the decrease of interface friction angle compared to internal friction angle is comprised between 2.36° and 9.98°.

The results obtained for K1G under three normal stresses were analyzed to obtain the required shear strength parameters. The typical shear stress-

Table 6 Test results on K1, CG and K1G for soil–solid interface

Test	ϕ (°)	Δ (mm)
<i>(a)</i>		
K1SI1	14.20	1.52
K1SI2	18.84	4.51
K1SI3	23.40	4.31
K1SI4	24.87	3.31
K1AI1	17.45	3.31
K1AI2	18.66	2.91
K1AI3	19.58	2.72
K1AI4	20.17	3.51
<i>(b)</i>		
CGSI1	8.18	0.30
CGSI2	10.21	2.02
CGSI3	10.90	2.52
CGSI4	12.43	2.31
<i>(c)</i>		
K1GSI1	10.87	0.81
K1GSI2	17.45	2.91
K1GSI3	21.53	2.92
K1GSI4	23.84	4.92

horizontal displacement curves are illustrated in Fig. 7. The internal friction angle deduced is 24.56°. The frictional angle for rough interface obtained varies between 17.45° and 23.84°. Compared to the values obtained when soil–soil shearing is involved, the interface friction angles are lower; the reduction varies between 13.6° and 0.7°. As expected, the friction angles of the soil-smooth steel interface (SI1), were considerably lower (i.e. 14.62° for K1, 8.18° for CG and 10.8 for K1G). The values of the ratio δ/ϕ are reported in Table 7. It is noticed that these values are ranging between 0.56 and 0.98 for K1, 0.44 and 0.67 for CG and 0.44 and 0.97 for K1G.

3.1.2 Discussion of Results

The variation of δ/ϕ with respect to R_a is shown in Fig. 8. According to the curves trend, it can be clearly seen that the friction ratio increases with increasing R_a . The increase tendency is more or less the same for K1 and K1G for rough interfaces whose R_a values are greater than about 8 μm . However, for lower values, distinct curves portions are noted. On the other hand, CG presents lower values of δ/ϕ and seems to have a value of 0.7 as upper limit.

It is also noted that the type of material used (steel or abrasive paper) does not have a major effect on the shear strength; this result is in a good agreement with the results obtained by Esashi et al. (1966), concerning three construction materials (steel, concrete and wood) and sand. It agrees also with the results presented by Frost and Han (1999) for steel and composite of reinforced fiber polymer. Hammoud (2006) also shows that the relationship between the interface friction coefficient and R_a is almost unique for the tested clays, regardless of the kind of interface material (steel or concrete).

In Fig. 9 which shows the influence of D_{av} on δ/ϕ , it is shown that the friction ratio increases with the average diameter particularly for SI2, SI3 and SI4. Regarding the smoothest interface (SI1), for diameters ranging from 3.5 to 12 μm , the friction ratio does not seem to be affected. As a result, the trend curve has a different shape compared to the curves corresponding to the rough interfaces.

Figure 10 shows the variation of δ/ϕ with relative roughness R which combines the influence of both R_a and D_{av} . It is shown that the friction ratio δ/ϕ increases with increasing relative roughness and for each type of soil there is a corresponding trend curve. Likewise, the increase tendency is also roughly the same for K1 and

Table 7 Values of δ/ϕ for K1, CG and K1G regarding soil–steel interfaces

Test	δ/ϕ
<i>(a)</i>	
K1SI1	0.56
K1SI2	0.74
K1SI3	0.92
K1SI4	0.98
K1AI1	0.68
K1AI2	0.73
K1AI3	0.77
K1AI4	0.79
<i>(b)</i>	
CGSI1	0.44
CGSI2	0.55
CGSI3	0.59
CGSI4	0.67
<i>(c)</i>	
K1GSI1	0.44
K1GSI2	0.71
K1GSI3	0.88
K1GSI4	0.97

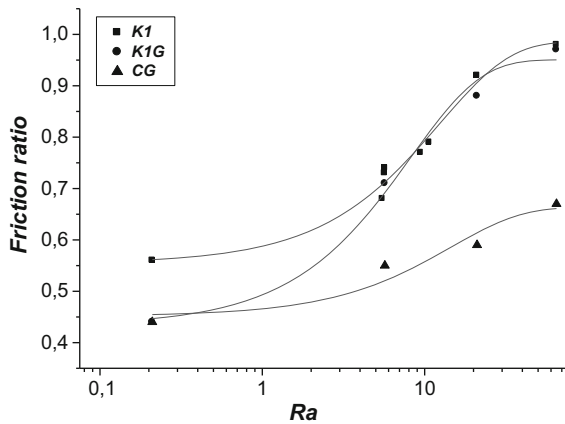


Fig. 8 Variation of δ/ϕ with R_a

K1G even for lower values. CG presents also, in the same manner as R_a , lower values of δ/ϕ and seems to have a value of 0.7 as upper limit as well.

From the curves obtained in Figs. 8 and 10, globally three modes of interface shearing are likely to be postulated:

- A mode in which sliding at the interface takes place (interface sliding) for smooth interfaces (i.e. low roughness). In this mode, the friction ratio is clearly smaller than that obtained in the case of a soil–soil shearing. Sliding is confined to the interface and only particles close to the interface surface are involved in the interaction between the soil and the interface. As a result, a thin shear

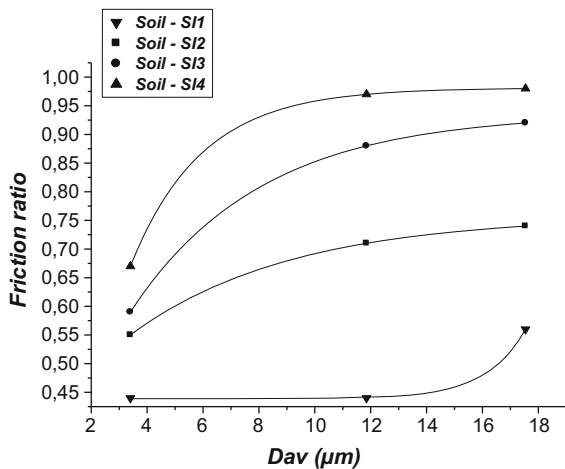


Fig. 9 Variation of δ/ϕ with D_{av}

surface may develop which gives a major difference between soil–soil and interface resistance. Sliding occurs along a solid material–soil contact surface as long as R_a and R are smaller than critical values equal to about 1 or 0.1 respectively, for K1 and K1G (i.e. $R_a = 0.1D_{av}$). For CG, in this mode, the upper limit is either $R_a \approx 3 \mu\text{m}$ or $R \approx 1$ (i.e. $R_a \leq D_{av}$).

- A mode in which shearing takes place within the soil if the values of R_a or R are greater than 11 or 2 respectively for K1 and K1G (i.e. for $R_a \geq 2D_{av}$). Beyond this threshold, the effect of roughness is then practically negligible and the shear strength is of the same magnitude of the internal shear strength of the soil. For this mode the upper limit of friction ratio is equal to unity ($\delta/\phi = 1$). It is believed that shearing at the interface resulted in the development of a horizontal thin slip surface within the sample body. More particles in the sample (not limited to particles close to the interface surface) tend to be involved in the shearing process. However for CG soil–steel friction, this mode does not seem to exist for the range of interfaces tested.
- As far as K1 and K1G are concerned, an intermediate mode (mixed behavior) for interfaces of intermediate roughness for which $R_a = 1$ to 11 or $R = 0.1$ to 2. For CG, this mode takes place when $R_a \geq 3$ or $R \geq 1$. In this mode there is a clear increase of interface friction with roughness, as indicated in Fig. 10. It is suggested that a thin layer of soil is likely to stick to the solid material in place causing both soil–soil as well as soil–solid materials shearing to take place simultaneously.

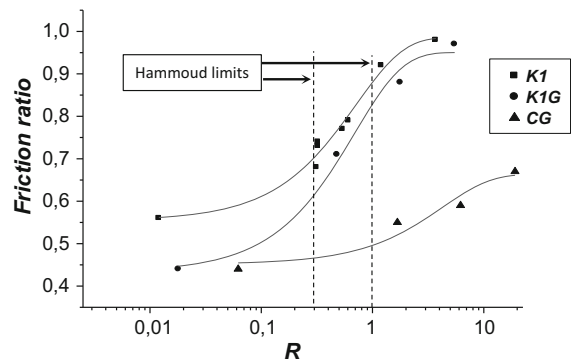


Fig. 10 Variation of δ/ϕ with R

The modes of interface shearing suggested above have been also postulated by Tsubikihara et al. (1993) who tested cohesive soils against mild steel interfaces, using a direct simple shear type of test apparatus, for displacements of 15 mm. They concluded that the frictional behavior can be classified into three failure modes: full sliding at the interface, shear failure within the soil, and mixed behavior where interface sliding and shear deformation of the soil specimen proceed simultaneously. For shearing at the interface soil–steel with values of R_{max} ($L = 0.2$ mm) of 20 and 30 μm , interface sliding and shear deformation proceed simultaneously.

It is noted that similar results of interface shearing obtained by Hammoud (2006) regarding tests conducted by means of ring shear tests in the Bromhead ring shear apparatus on four kinds of cohesive soils and two interface materials (i.e. steel and concrete) with different roughness, sheared to large displacements. However, for peak values, he obtained a unique tendency curve for the variation of δ/ϕ with R . Consequently, he concluded that the frictional behavior can be classified into three failure modes:

- Full sliding at the interface when R , is smaller than 0.3;
- Shear failure within the soil when R is greater than 1;
- Mixed behavior where interface sliding and shear deformation of the soil specimen occurs simultaneously, for values of R in the range 0.3–1.

As can be noticed the delimitations between the three modes of interfacial shearing are different. They seem to be dependent on soil type. Figure 11 illustrates the three modes of soil–solid material interface friction shearing.

3.2 Effect of Texture Model

3.2.1 Test Results

As mentioned previously, four types of roughness textures, namely TX1, TX2, TX3 and TX4, which have a value of $R_a = 5.69$ μm , have been used to study their effect on the interface shear strength. The mode of interface shearing is then an intermediate one. Figure 12 shows the relationship between shear stress and horizontal displacement for each texture model. The curves were established for three levels of normal

stresses: 109, 150 and 204 kPa. It can be seen that the relationship between shear stress and horizontal displacement is more or less hyperbolic with little hardening when soil–soil shearing is involved.

It can be also noted that the curves of tests corresponding to the interfaces TX1, TX2, TX3 and TX4 have generally similar trends, a part from K1, with almost the same peak shear stress. A brittle behavior has been highlighted especially for CG. The curves corresponding to soil–soil shearing show the highest shear stresses with no clear peak value. In addition, for interface shearing, less shear displacement is necessary to reach peak conditions.

3.2.2 Discussion of Results

In order to assess the effect of texture model of steel surface on the interfacial maximum shear stress at failure, the results are presented in Fig. 13. As observed, it was found that the relationships are approximately linear for the range of normal stresses used. Furthermore, it can be noted that there is practically no effect of the texture models on the shear resistances measured. The results are also presented in Figs. 14 15 and 16 in the form of column charts which consist of four categories; each one representing one type of texture surface. They show the shear stress for four texture surfaces at normal stresses of 109, 150 and 204 kPa. Once again, as concluded before, no trend was observed regarding the values of τ which appear not to be affected by the texture model, regarding the interface shearing mode characterizing the interface used (i.e. the mixed behavior).

It is noted that similar results were reported by Dejong et al. (2001) for a sandy soil who examined the criteria of failure and the effect of texture which took place during a CPT penetration test and found the

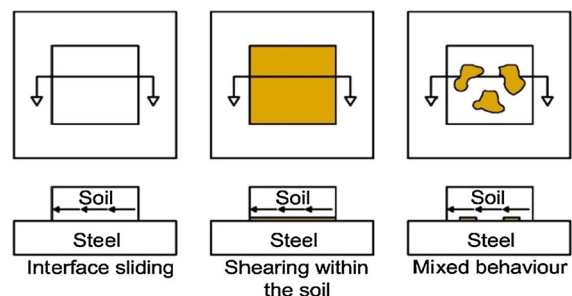


Fig. 11 Modes of interface friction shearing

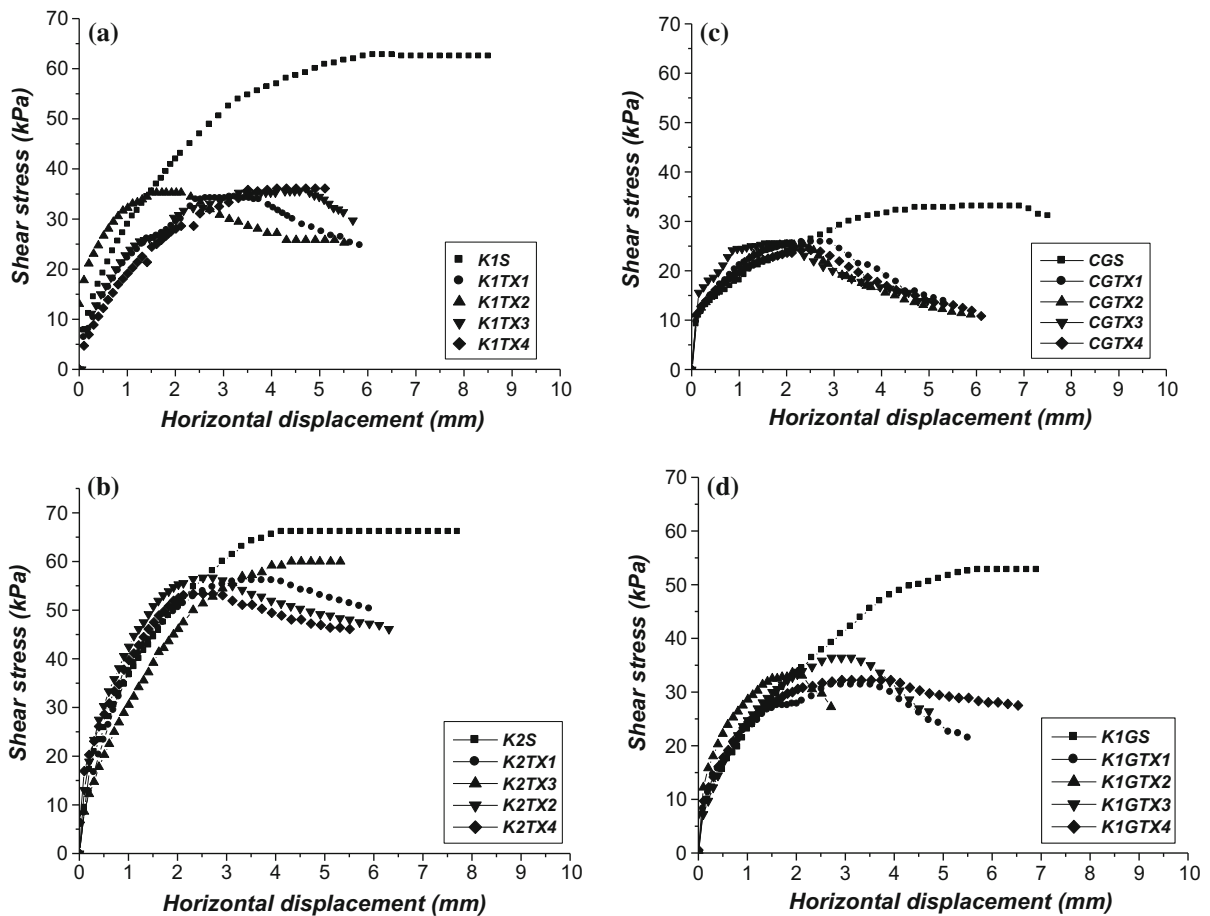


Fig. 12 Relationship between shear stress and horizontal displacement of texture models at 109 kPa

same values of δ for two different textures. Likewise, Tan et al. (2008) conducted interface tests by means of a modified direct shear apparatus on a saturated kaolin clay for two types of texture interface and found approximately the same values of interface angles, although the shearing mechanism was different in each case.

4 Conclusions

The objective of this research is to investigate the shear characteristics of cohesive soils by performing interface tests, under consolidated drained shear conditions, using a modified direct shear apparatus. Tests were performed with variations on interface roughness, material and texture. The following conclusions may be drawn:

For the studied interfaces, the shear strength of the cohesive soils tested is greater than that of the soil–solid material interface for similar stress conditions.

The ratio δ/ϕ increases with increasing roughness and varies according to soil type. It is ranging between 0.56–0.98 for K1, 0.44–0.67 for CG and 0.44–0.97 for K1G. Furthermore, the values of δ/ϕ which were plotted against R showed that there is not a single empirical relationship which fit the data pertaining to the three soils studied.

An interface friction behavior based on three modes namely full sliding at the interface, shear failure within the soil, and a mixed behavior where interface sliding and deformation of the soil specimen proceed simultaneously has been proposed. The limits between each mode depend on the soil type.

For CG which is classified as high-plasticity clay, the second mode of shearing (i.e. shearing within the

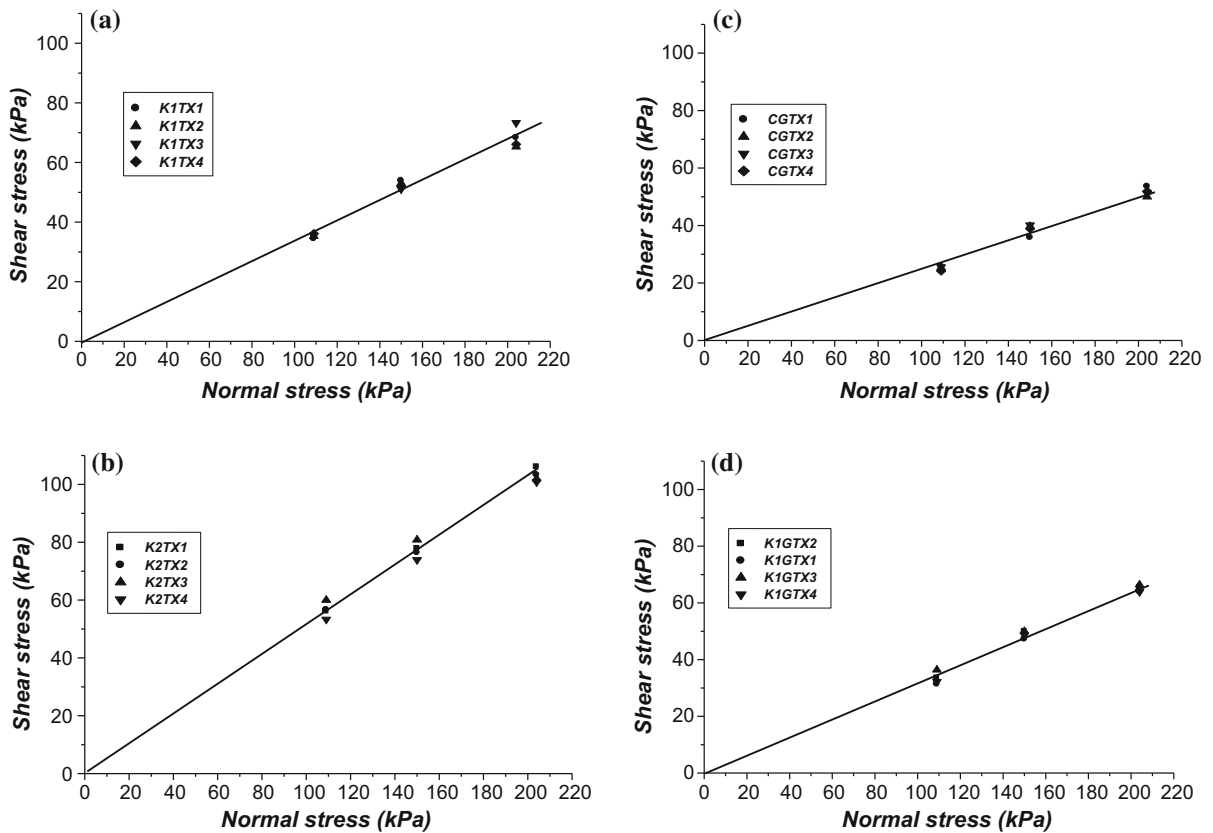


Fig. 13 Typical shear stress–normal stress relationship of soil–steel texture interface

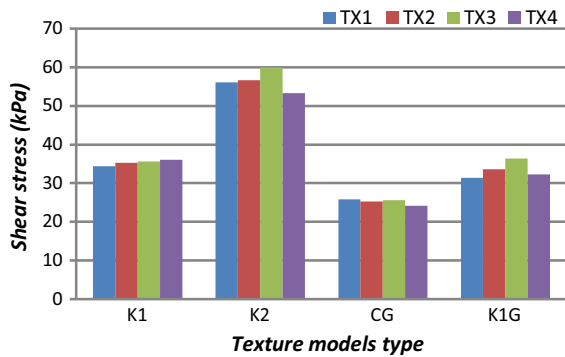


Fig. 14 Column charts of Interface shear stress for different models of steel texture at $\sigma_n = 109$ kPa

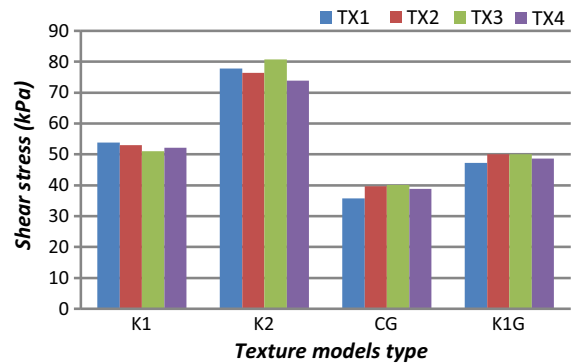


Fig. 15 Column charts of Interface shear stress for different models of steel texture at $\sigma_n = 150$ kPa

soil) has not been highlighted and the shear strength at the interface soil–steel is lower than the shear strength of the soil.

The type of material used (steel or abrasive paper) does not seem to have a major effect on the interface shear strength.

The shear strength of the soil tested is not dependent on the texture interface models. The interfaces roughness used in this investigation has a behavior which falls within the mixed interface one. Further research is needed to investigate whether the two others modes of interface behavior (i.e. interface

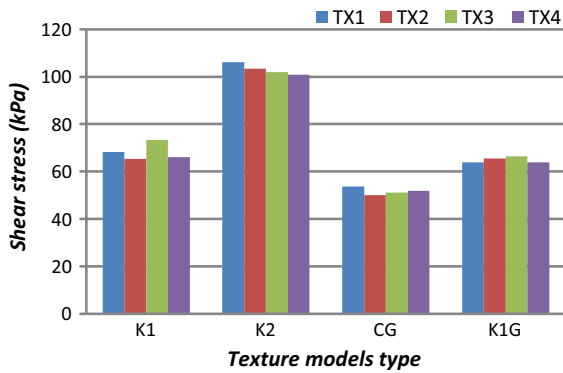


Fig. 16 Column charts of Interface shear stress for different models of steel texture at $\sigma_n = 204$ kPa

sliding and shearing within the soil) give the same results.

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