Effect of temperature on the shear strength of soils and the soil–structure interface

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Abstract

In the present work, shear behaviour of soils and soil/concrete interface is investigated through direct shear tests at various temperatures. Conventional direct shear apparatus, equipped with a temperature control system, was used to test sand, clay and clay/concrete interface at various temperatures (5°C, 20°C and 40°C). These values correspond to the range of temperatures observed near thermoactive geostructures. Tests were performed at normal stress values ranging from 5 kPa to 80 kPa. The results show that the effect of temperature on the shear strength parameters of soils and soil/concrete interface is negligible. A softening behaviour was observed during shearing of clay/concrete interface, which was not the case with clay specimens. The peak strength of clay/concrete interface is smaller than the ultimate shear strength of clay.

Keywords: shear strength; temperature; soil/structure interface; friction angle; thermoactive geostructure.

1. Introduction

Thermo-mechanical behaviour of soils has been a major research topic during the past two decades. The studies cover underground structures which are subjected to thermal changes including radioactive waste disposal, thermoactive geostructures, oil recovery, petroleum drilling, high-voltage cables buried in soils (Cekerevac 2003; Brandl 2006; Abuel-Naga et al. 2007; Hueckel et al. 2009; Cui et al. 2009). In these contexts, several works focus on the effect of temperature on the shear strength of soils but they are mainly limited to the temperature range of 20°C - 100°C (Hueckel & Pellegrini 1989; Hueckel & Baldi 1990; Robinet et al. 1997; Burghignoli et al. 2000; Graham et al. 2001; Cekerevac 2003; Ghahremannejad 2003). In the case of thermoactive geostructures, such as retaining walls or pile foundations, the soil temperature can vary from 5°C to 40°C (Brandl 2006; Boënnec 2009; Yavari et al. 2014*a*). However, few works investigate the effect of temperature on the shear strength of soil for this range of temperature.

In terms of temperature effect on shear strength, conflicting results could be detected from the literature review. Hong et al. (2013) argued that the effects of temperature on shear strength of clay are strongly dependent on the volume change induced by heating. On one hand, thermal expansion leads to a decrease of soil strength; on the other hand, the thermal contraction hardens the soil and makes the shear strength increase. According to Hamidi et al. (2014), heating could make the soil friction angle decrease, increase or stay unchanged. The soil shear behaviour is found to be dependent on its mineralogy, the loading history and the applied experimental method.

While various studies focus on the thermo-mechanical behaviour of clay, few works investigate the thermal effect on sand. Thermal consolidation tests performed by Recordon (1993) on fine sand in the range of 2°C and 40°C show that the compressibility parameters (compression index, modulus and over-consolidation ratio) are independent of temperature. The same observation was made by Saix et al. (2000) on clayey silty sand between 30°C and 70°C.

Direct shear tests have been widely used to evaluate the shear behaviour of soil and soil/structure interface. After Lemos and Vaughan (2000), shear strength of sand/structure interfaces, always smaller than that of sand, mainly depends on the roughness of the interface. When this latter is similar to the grains size, the sand/structure shear strength will approach to that of sand. For clayey soils, the residual shear strength at interface is close to that of clay and it does not depend on surface roughness.

In the case of thermoactive geostructures, heat exchange between the geostructures and the surrounding soil might influence the behaviour of the soil/structure interface. Interface behaviour, which is already of complex nature, is therefore a major concern in thermoactive geostructures under the coupled thermo-mechanical loadings. However, few works consider the effect of temperature on the shear behaviour of soil/structure interface (Di Donna and Laloui 2013; Murphy and McCartney 2014; Di Donna et al. 2015).

In this study the effect of temperature on shear strength behaviour of soils and soil/structure interface is extended to the range of low temperatures (5°C – 40°C) pertinent to the case of thermoactive geostructures. Direct shear box, equipped with temperature control system, was used to test sand, clay and clay/concrete interface under rather small normal stresses (5 – 80 kPa).

2. Experimental techniques and materials used

A direct shear apparatus, equipped with a temperature control system, was used to investigate the shear behaviour of soil and soil/concrete interface. A general view of the system is shown in Figure 1. A copper tube was accommodated in the shear box container and connected to a heating/cooling circulator. Water with controlled temperature circulates inside the copper tubes via the circulator. These tubes are immersed in water inside the shear box. This system allows controlling the temperature of the soil specimen inside the cell without altering the mechanical parts of the cell. The heating/cooling circulator, a cryostat, is able to impose a temperature in the range of -20°C to 80°C. Two thermocouples were installed in the box: one below the shear box and the other at the water surface. The container was thermally insulated using expanded polystyrene sheets. The soil (or soil/structure) was sandwiched between two porous stones and two metallic porous plates. A preliminary test was performed to verify the temperature homogeneity in the container during thermal loading paths. Two thermocouples were inserted inside the soil specimen and the temperature of the cell was changed following the same rate that was applied latter in the mechanical tests. The results show that the temperature inside the specimen is similar to that inside the container (Figure 2) confirming the temperature homogeneity of the system (the imposed temperature is that of water in the heating/cooling circulator outside the shear apparatus). For the direct shear tests, the thermocouples inside the shear box were not used in order to avoid its possible influence on the specimen's mechanical behaviour.

In the present work, tests were performed on Fontainebleau sand, Kaolin clay, and Kaolin clay/concrete interface. Actually, literature review shows that the effect of temperature can be expected on the strength parameters of clay and clay/concrete interface while the behaviour of sand is independent of temperature in the range of 5°C – 40°C. Testing sand at various temperature in this study is helpful to evaluate the performance of the testing device and the repeatability of the experimental procedure. The physical properties of Fontainebleau sand are: particle density ρ_s = 2.67 Mg/m^3; maximum void ratio e_{max} = 0.94; minimum void ratio e_{min} = 0.54 (De Gennaro et al. 2008); and mean diameter D_{50} = 0.23 mm. The grain size distribution of the sand used is shown in Figure 3. To perform direct shear test, dry sand was directly poured into the shear box and slightly compacted to a density of 1.50 Mg/m^3. This value, corresponding to a relative density of 46%, is similar to that in the works of De Gennaro et al. (2008), Kalantidou et al. (2012), and Yavari et al. (2014*b*). After the compaction, distilled water was added to the container to fully saturate the sand specimen and to immerse the shear box.

The Kaolin clay has a liquid limit w_L = 57%, a plastic limit w_P = 33%; and a particle density ρ_s = 2.60 Mg/m^3 (Frikha, 2010). The grain size distribution of Kaolin clay, obtained by laser diffraction method, is shown in Figure 3. To prepare a soil sample, the clay powder was first mixed with distilled water at 1.5w_L and then consolidated in an oedometer cylinder (with an internal diameter of 100 mm) under a vertical stress of 100 kPa. At the end of the consolidation phase, the soil sample (having a void ratio of 1.35) was removed from the cylinder and cut into blocks of dimensions 60 x 60 x 20 mm and inserted into the shear box for testing the shear behaviour of clay.

To test the clay/concrete interface the thickness of the sample was reduced to 10 mm. A piece of concrete with the thickness of 10±2 mm was cut and solidly fixed to the lower half of the shear box. The maximum roughness detectable by the naked eye is in the order of 0.7 mm (see Figure 4). It should be noted that the same piece of concrete was used in all tests in order to maintain a similar roughness. Actually, as the test was performed only with clay (not with sand) and under low stresses, the roughness of the concrete surface was assumed to remain intact after the tests.

The loading paths applied are shown in Figure 5. For each test, after the installation of the system, a normal stress of 100 kPa was applied to the sample (path A-B); this value is equal to the pre-consolidation pressure of the clayey sample. Thus, applying such normal stress does not significantly modify the soil porosity (for both sand and clay). Note that this loading was applied by steps of 20 kPa. Load was increased once the vertical displacement stabilised. The range of stress considered in this study mainly corresponds to shallow geostructures (retaining walls, shallow foundations) or small-scale tests. Actually, most of the works on the thermo-mechanical behaviour of soils have been performed at higher stress range (which mainly corresponds to deep geostructures).

The soil temperature was then increased from the initial value (20°C) to 40°C by increments of 5°C (path B-C). Each increment was kept for 15 minutes. The results of this part show that vertical displacement stabilised within this period. Overall, it could be stated that the soil temperature changed by 20°C in 3 h (with an average rate of 7°C/h). Once temperature reached 40°C, it was kept constant for two hours in order to permit the dissipation of excess pore water pressure induced by heating. This value of 40°C corresponds to the maximum value of temperature tested in the present work. For shearing tests at 40°C (Figure 5*a*), the normal stress was decreased to the desired value (path D-E) prior to shearing. For shearing tests at 20°C (Figure 5*b*) and 5°C (Figure 5*c*), the soil temperature was first incrementally decreased to the desired temperature (path C-D). Each increment, of 5°C, took approximately 30 minutes. Cooling was performed at almost the same rate as heating (7°C/h). Finally, the normal stress was decreased to the desired value (path D-E) prior to shearing.

Such specific stress path has been chosen to ensure that all the shearing tests start from the thermo-elastic domain and at similar soil densities. As a result, the effect of temperature and normal stress on the shear behaviour would be better detected, without coupled effects induced by thermal consolidation. Actually, the point C in the stress path (100 kPa of normal stress and 40°C) corresponds to the maximum temperature and normal stress that the soil specimen has been subjected to prior to shearing.

For the tests on clay or clay/concrete interface, shearing rate should be small enough in order to ensure that no excess pore pressure was generated during the test and the sample was sheared under drained conditions (AFNOR, 1994; ASTM 1998). The shear rate chosen, 14 μm/min, is small enough to avoid the effect of shear rate on the soil behaviour following the work of Bhat et al. (2013).

For granular soils the shear rate could be higher because the consolidation is faster. In the tests on sand the shear displacement was applied at the rate of 0.2 mm/min. The maximum shear displacement at which shearing stops is set to 6 mm. This value is 10% of the soil specimen size in the shear direction.

3. Experimental results

Results of tests on sand are shown in Figures 6-8. Under each normal stress and each temperature two tests were conducted in order to check the repeatability of the experiments. For the tests at 5°C, as could be seen in Figure 6*a* the shear stress increases with horizontal displacement increase and the failure is of ductile type. Figure 6*b* shows the vertical displacement during the shear process. The results show a contracting phase followed by a dilating one under higher normal stresses. At low normal stresses, the soil at the interface tends to dilate from the beginning to the end of the shear process. It can be noted that the repeatability of the results on vertical displacement was quantitatively less than the shear stress. Maximum shear strength observed as a function of normal stress is shown in Figure 6*c*. The maximum shear stress and the normal stress can be well correlated with a linear function and a friction angle of 36° can be then determined from these results (with no cohesion).

Experimental results on sand at 20°C are shown in Figure 7. As in the case of 5°C, the behaviour is of ductile type and the peak behaviour was observed only in one test at 80 kPa of normal stress. The vertical displacement behaviour (Figure 7*b*) is similar to that at 5°C; under normal stress of 80 kPa and 40 kPa, soil tends to contract at the beginning and it dilates afterwards, while under lower normal stresses it tends to dilate from the beginning. The shear strength envelope is shown in Figure 7*c*. A very good agreement between tests under the same normal stress value could be detected at 5, 10 and 40 kPa. Friction angle is equal to 35° and soil is almost cohesionless.

The results of tests at 40°C are exhibited in Figure 8. Similar observations to that at 5°C and 20°C can be derived: discrepancy on the vertical displacement/horizontal displacement curves (Figure 8*b*); good repeatability on the peak strength/normal stress plot (Figure 8*c*); a linear correlation between the shear strength and the normal stress with a friction angle of 35° and a zero cohesion.

Results on clay and clay/concrete interface at 5°C are shown in Figure 9. In Figure 9*a*, clay/concrete interface shows a softening behaviour after the peak, while the shear stress increases continuously for clay. At a given normal stress, the shear stress/displacement curves of the two cases are quite similar before the peak. Results on vertical displacement versus horizontal one are shown in Figure 9*b*. For both clay and clay/concrete interface tests, under 40, 80 and 100 kPa, the soil shows a contracting trend while a dilating phase could be detected at lower stresses. Vertical displacement of clay is almost twice higher than that observed on clay/concrete interface under the same normal stress. Peak and ultimate shear strength of clay and that of clay/concrete interface are shown in Figure 9*c*. The results show that the strength envelope of clay situates above that of clay/concrete interface.

Results at 20°C are shown in Figure 10. The same observation as at 5°C (Figure 9*a*) is valid for Figure 10*a*. In addition, the fragile failure type of clay/concrete interface is more pronounced under normal stress values of 40, 80 and 100 kPa. Figure 10*b* shows that the vertical displacement of clay/clay is about twice higher than that of clay/concrete interface. At 40, 80 and 100 kPa of normal stress the soil volume tends to contract while it dilates at lower normal stresses. Peak and ultimate shear strength envelopes are shown in Figure 10*c*. As at 5°C, the ultimate shear strength of clay/concrete interface, at the same normal stress, is approximately 10% lower than that of clay.

Results on shear stress versus horizontal displacement of clay and that of clay/concrete interface at 40°C are exhibited in Figure 11*a*. As in the cases at 5°C and 20°C, the fragile type failure is observed for clay/concrete interface while a ductile type is observed for clay. Results on vertical displacement versus horizontal at 40°C are shown in Figure 11*b*. In both clay/concrete interface and clay/clay tests, under 40, 80 and 100 kPa, sample tends to contract during the shear process while dilation is observed at smaller normal stresses. The difference between the shear envelope of clay and the peak-strength envelope on clay/concrete interface is quite small at 40°C (Figure 11*c*).

In order to evaluate the effect of temperature on shear strength parameters (friction angle and cohesion), all the results obtained are shown in Figure 12. It should be noted that the effect of temperature on the friction angle is quite small and the trend is not clear (Figure 12*a*). For sand, the friction angle decreases slightly from 5°C to 20°C, while in the range of 20°C and 40°C it does not change. Effect of temperature on the friction of angle of clay and the ultimate friction angle of clay/concrete interface is similar; it slightly increases from 5°C to 20°C and decreases from 20°C to 40°C. The friction angle of clay is higher than the peak-strength friction angle of clay/concrete (except at 40°C). The cohesion measured on clay and clay/concrete interface is quite small, few kPa (Figure 12*b*) with small variation between 5°C and 40°C.

Discussion

All the tests on sand have been duplicated. The results show good repeatability in terms of shear stress versus horizontal displacement. That allows obtaining reliable results in terms of shear strength. Nevertheless, the repeatability in terms of vertical displacement versus horizontal one is less obvious. Note that in direct shear test, only a very thin layer of soil (less than 1 mm, corresponding to the distance between the two halves of the box) is subjected to shearing. Actually, the vertical displacement is related to the volume change of the sheared zone but the thickness of this latter can vary from one test to the other. For the tests on clay and clay/concrete interface that are more time consuming, only one test has been conducted at each temperature and normal stress. The relationship between the shear strength and the normal stress can be well correlated with a linear function, which allows determining the friction angle and the cohesion. These observations show equally the reliability of the obtained results.

In order to better analyse the effect of temperature on soils friction angle, the results of the present work are plotted together with that obtained from other works in the same figure (Figure 13). The results from the existing works show that the effect of temperature on soils is quite small. In addition, at higher temperature, the friction angle can be higher in some cases and lower in other ones. These observations are similar to that obtained in the present work.

The results on clay/concrete interface show a softening of the shear strength during shearing. In addition, the results indicate that the peak-strength friction angle of the clay/interface is slightly lower than that of clay (except at 40°C). As shown by previous works (Tsubakihara and Kishida 1993; Rouaiguia 2010; Taha and Fall 2013) the interface behaviour is dependent on the surface roughness. After Rouaiguia (2010), the relatively plane surface of concrete makes clay particles reorient easily once the maximum shear strength is reached. The particles would then be aligned in the developed sheared zone and the shear stress decreases. In the present work, vertical settlement of the clay sample was about twice of that of clay/concrete. That can be explained by the fact that the thickness of the sheared zone in clay/clay tests (distance between the two halves of the box) would be twice that of the clay/concrete interface tests (half of the distance between the two halves of the box).

In the works of Di Donna and Laloui (2013) and Di Donna et al. (2015) on clay/concrete interface, the shear resistance at 50°C is higher than that at 20°C. The interface friction angle reduces slightly at high temperature but the most significant thermal effect is found to be an increase of the cohesion. This was explained by the thermal consolidation of the clay during heating. In the present study, all the samples have been pre-consolidated to 100 kPa of vertical stress and heated to 40°C prior to the application of the initial conditions (lower stress and temperature between 5°C and 40°C). This procedure allows having soil sample at similar void ratio for all the tests. For this reason, the effect of temperature on the clay/concrete interface, which is mainly related to thermal consolidation, is negligible. In the work of Murphy and McCartney (2014), the tests were performed on unsaturated soil and the effect of temperature on the shear properties was not significant.

Conclusions

Shear behaviour of sand, clay and clay/concrete interface at various temperatures (5°C, 20°C, and 40°C) was investigated through direct shear tests. The following conclusions can be drawn:

- The shear stress behaviour of sand and clay show a hardening behaviour while that of clay/concrete interface show a softening one.
- At the same normal stress, the peak shear strength of clay/concrete interface is smaller than the shear strength of clay.
- The effect of temperature (in the range of 5°C – 40°C) on the shear strength of sand, clay and clay/concrete interface is negligible.

These findings would be helpful in designing thermoactive geostructures where the range of applied temperatures is similar and the effect of heating/cooling cycles on the shear strength at soil/structure interface might be significant.

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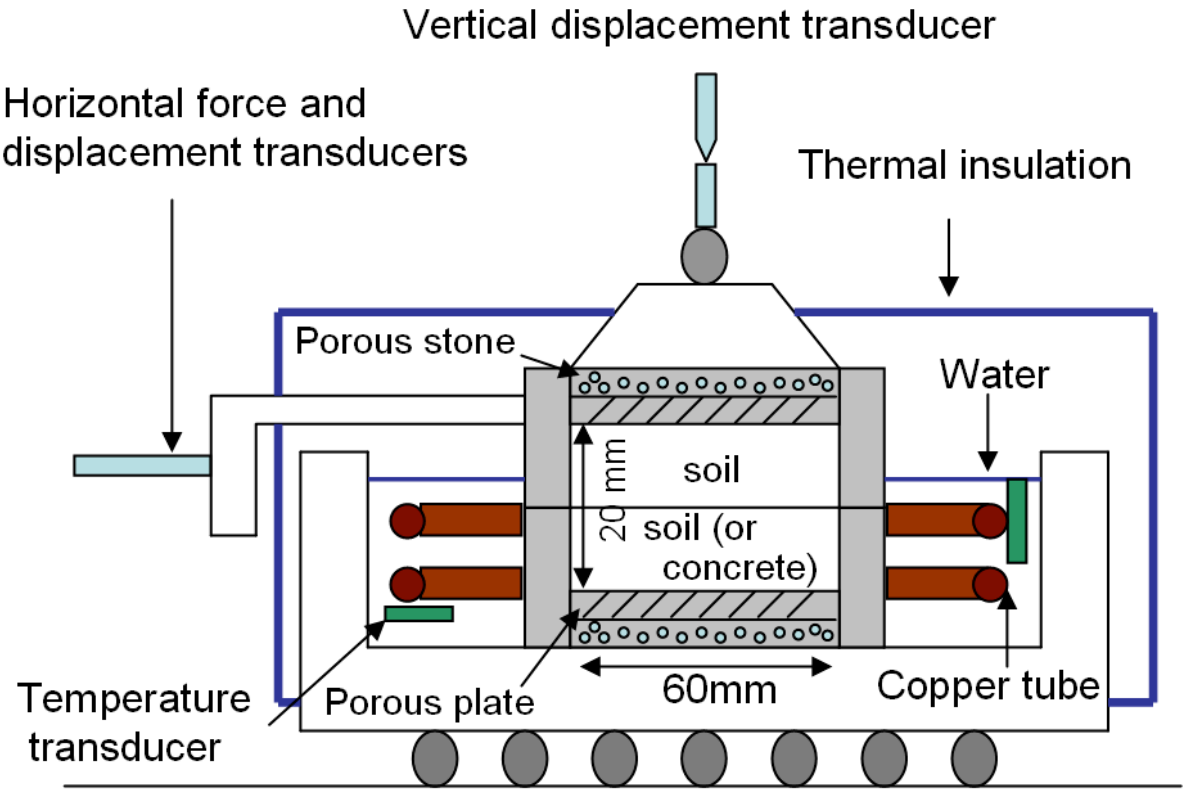

Figure 1. Direct shear apparatus with temperature control system

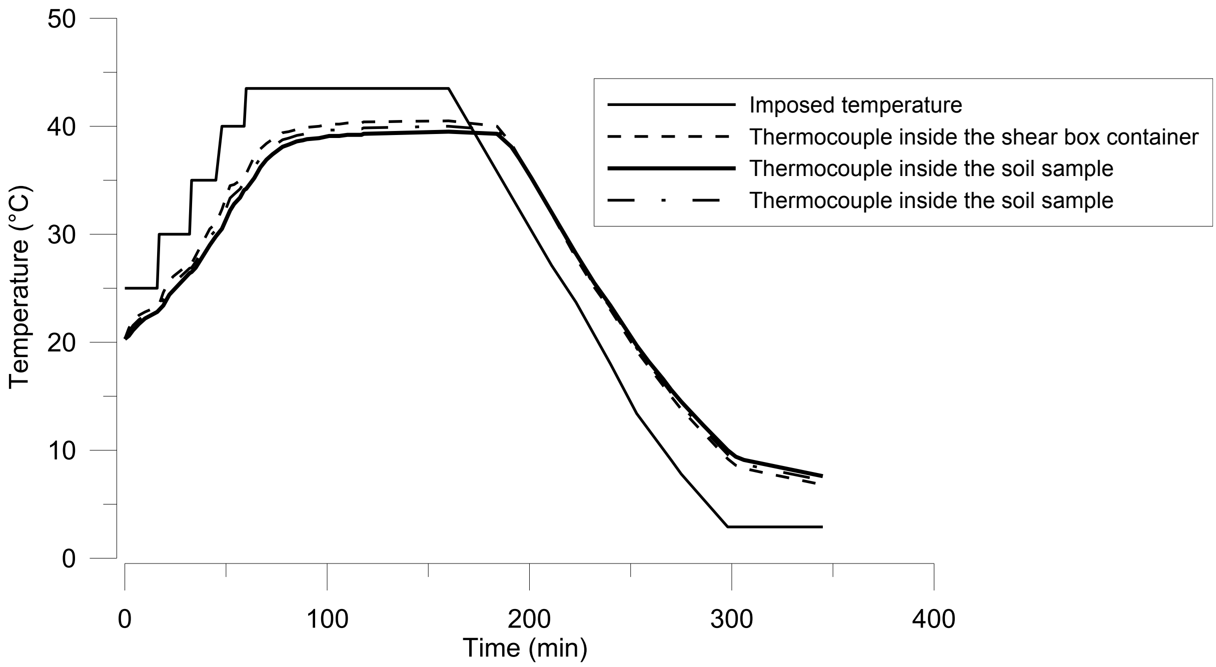

Figure 2. Results of preliminary tests for checking temperature homogeneity in the system.

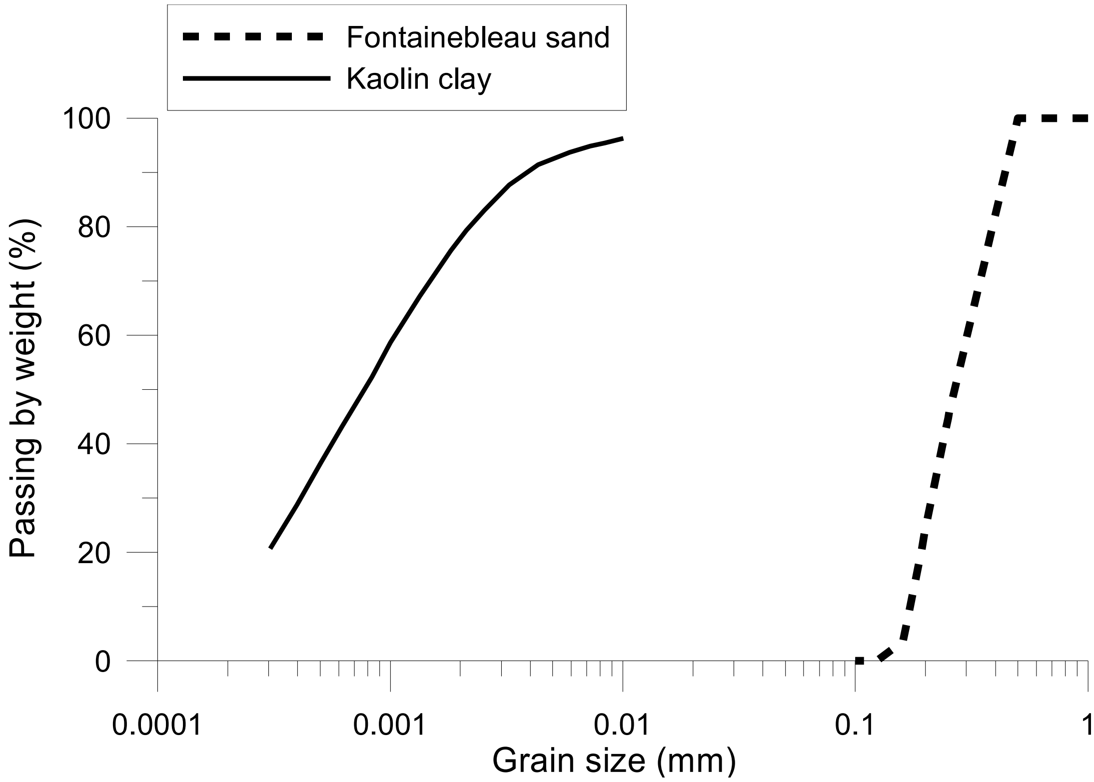

Figure 3. Grain size distribution curves of Fontainebleau sand and Kaolin clay

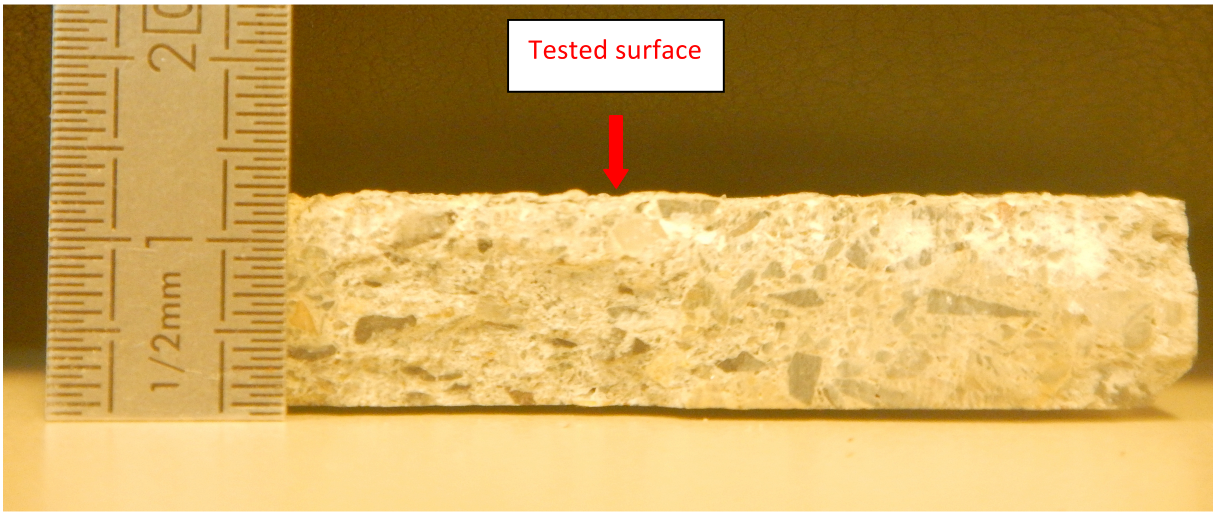

Figure 4. Concrete piece used for studying clay/concrete interface

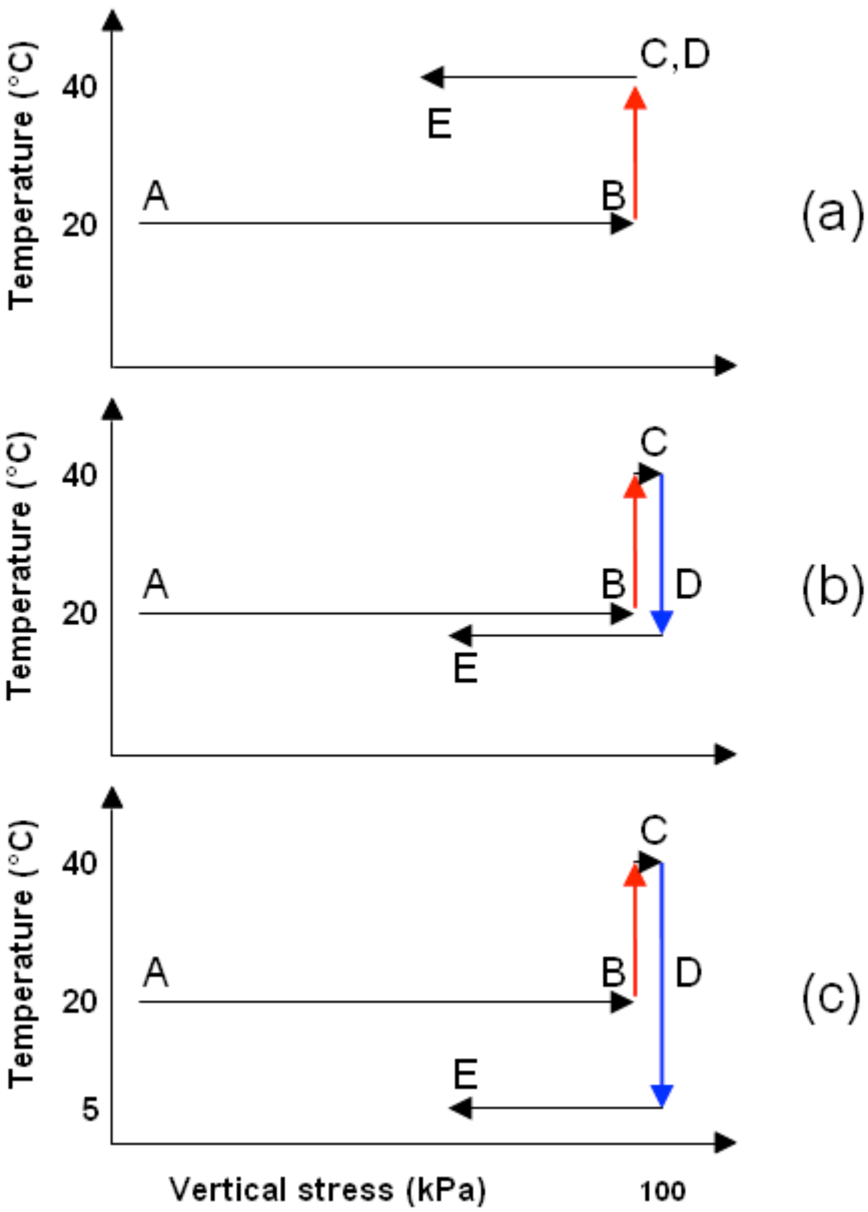

Figure 5. Thermo-mechanical paths: (a) tests at 40°C; (b) tests at 20°C; (c) tests at 5°C

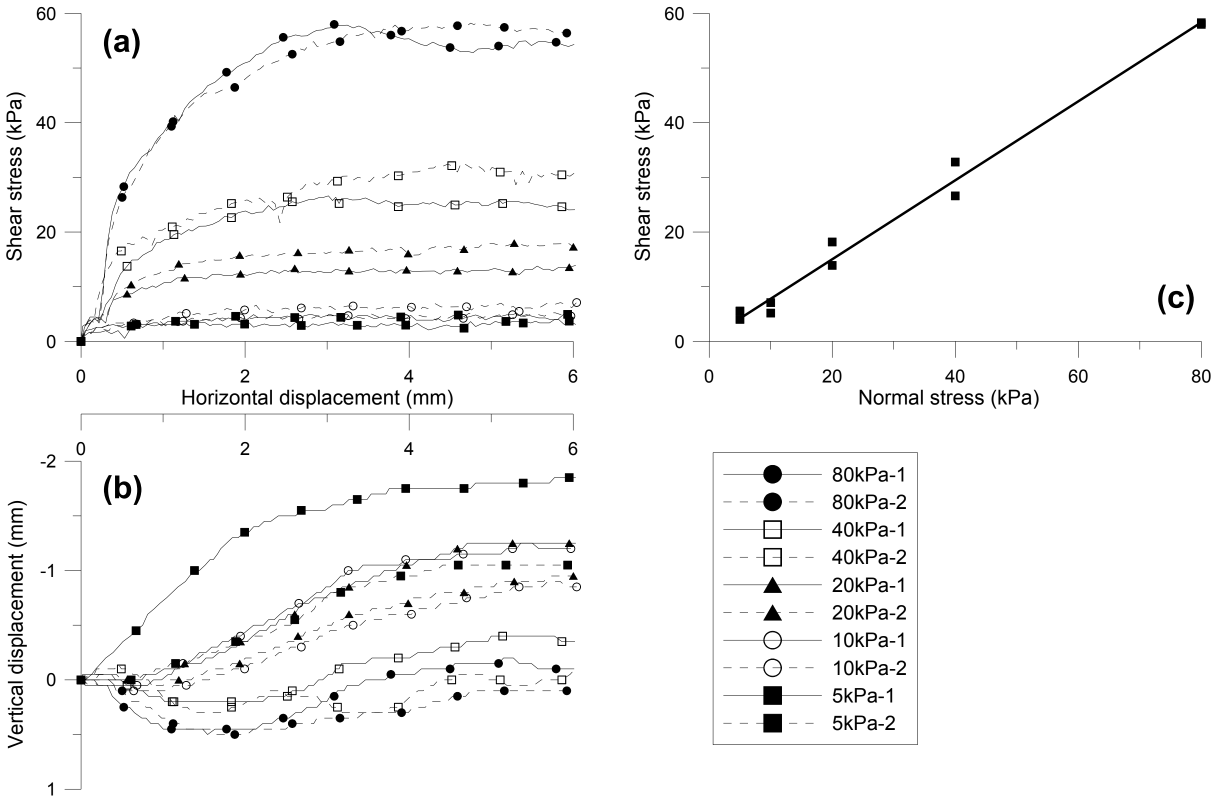

Figure 6. Experimental results on sand at 5°C: (a) Shear stress versus horizontal displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength envelope

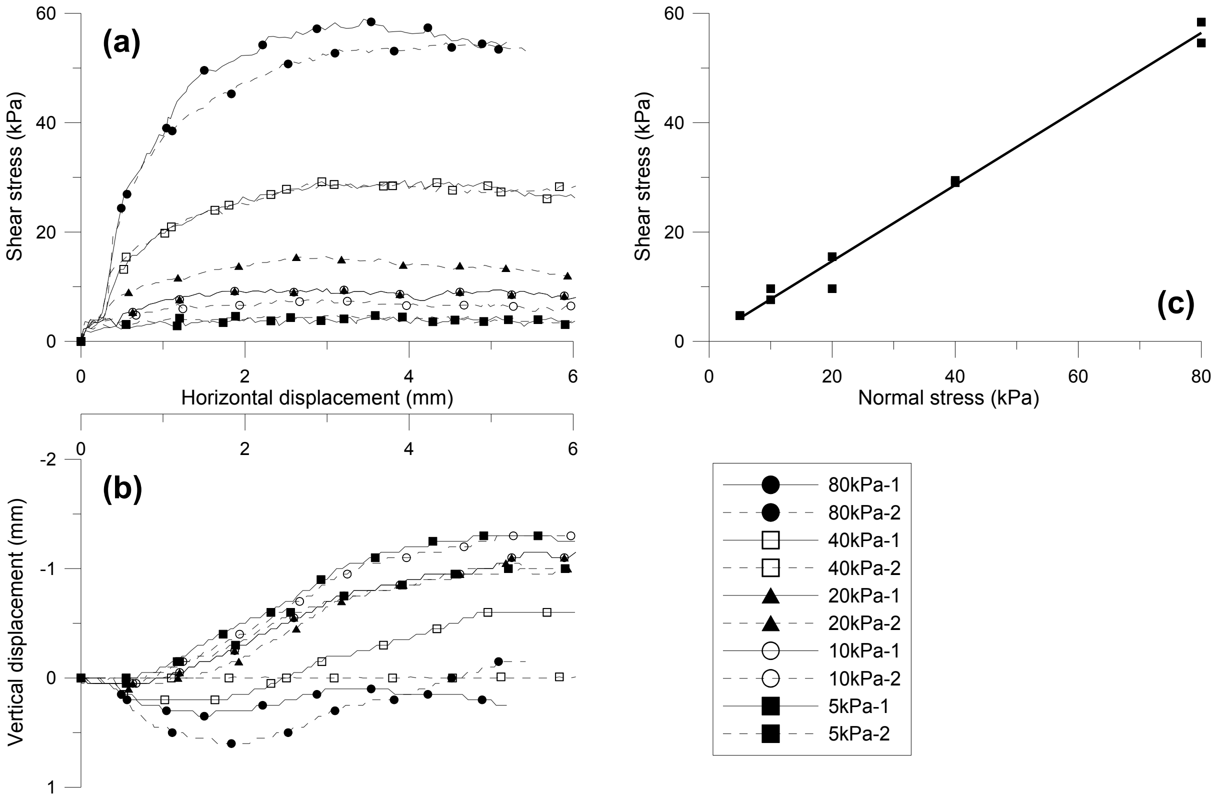

Figure 7. Experimental results on sand at 20°C: (a) Shear stress versus horizontal displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength envelope

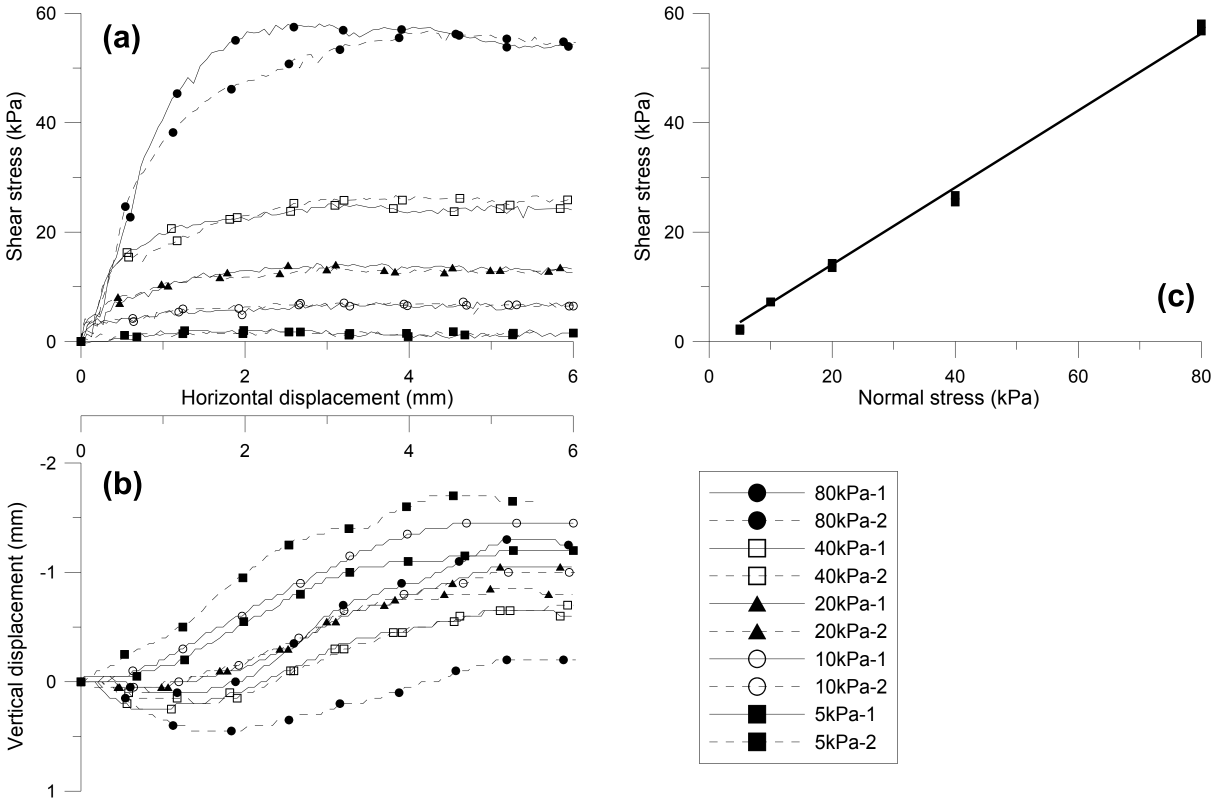

Figure 8. Experimental results on sand at 40°C: (a) Shear stress versus horizontal displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength envelope

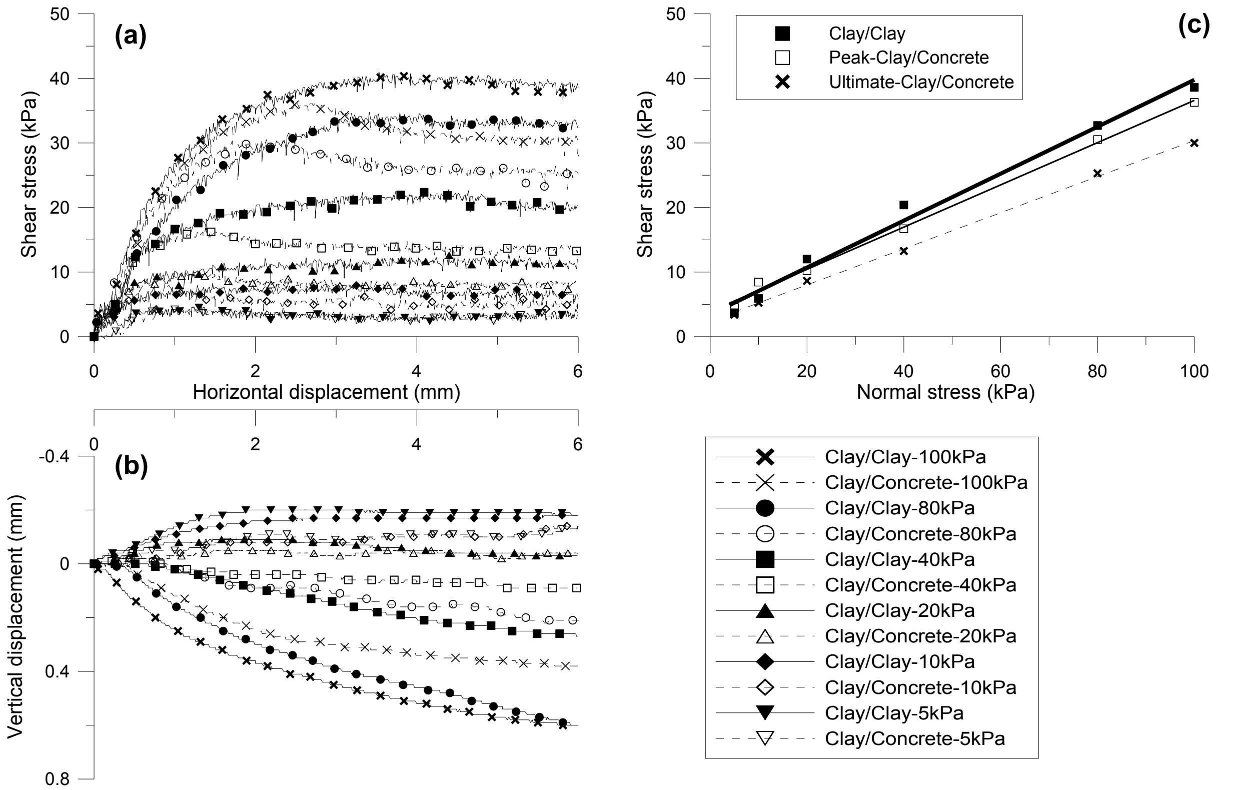

Figure 9. Experimental results on clay and clay/concrete interface at 5°C: (a) Shear stress versus horizontal displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength envelope

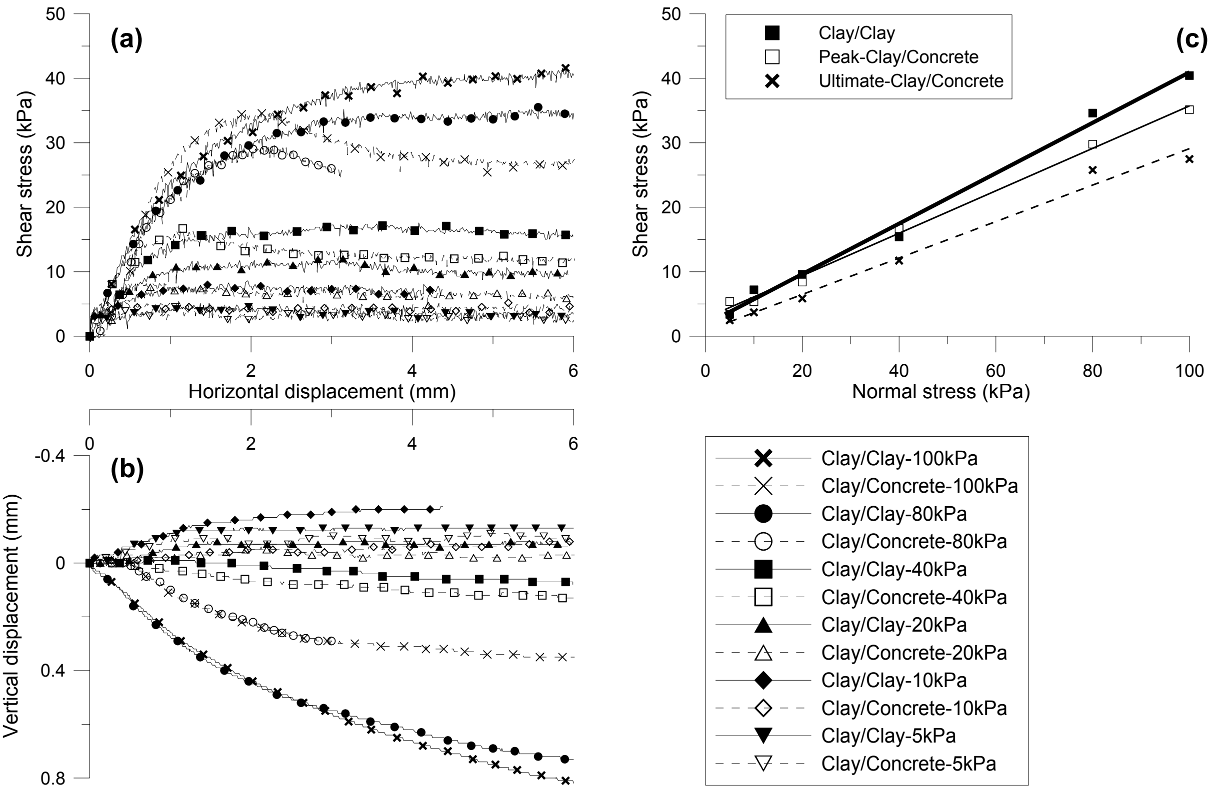

Figure 10. Experimental results on clay and clay/concrete interface at 20°C: (a) Shear stress versus horizontal displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength envelope

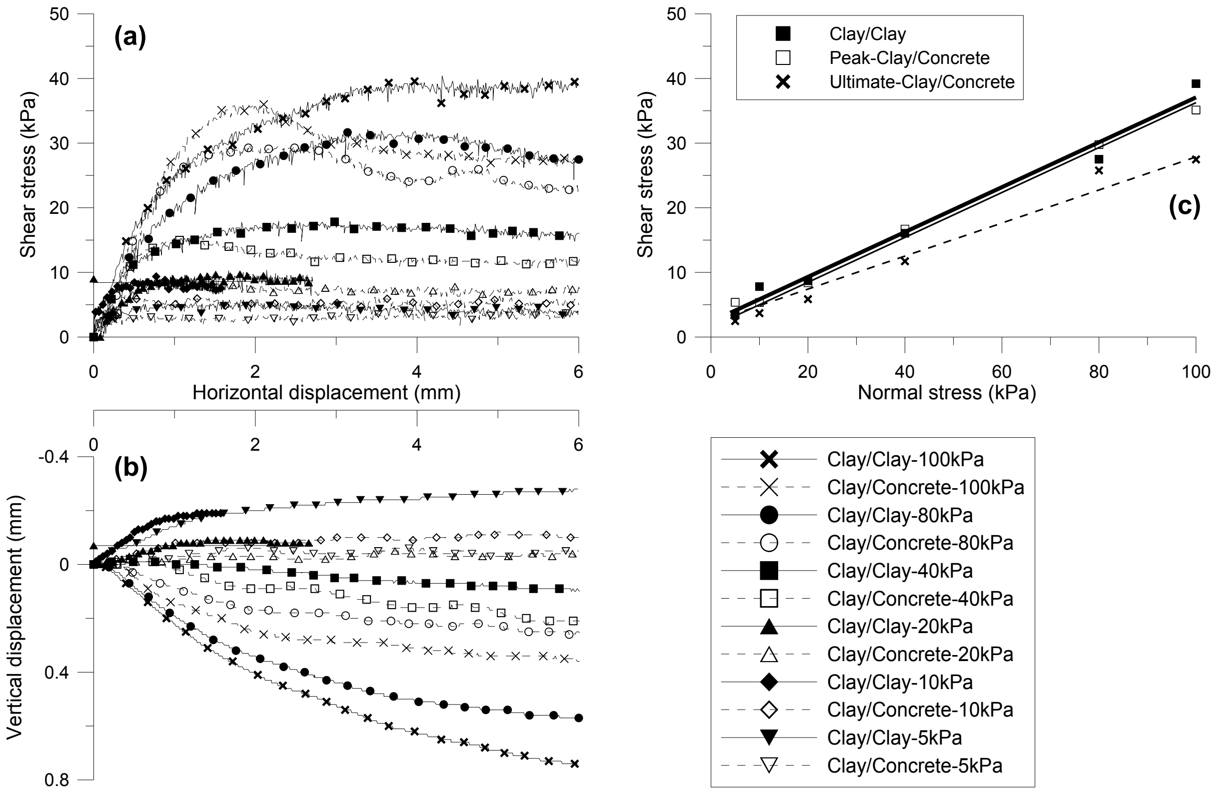

Figure 11. Experimental results on clay and clay/concrete interface at 40°C: (a) Shear stress versus horizontal displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength envelope

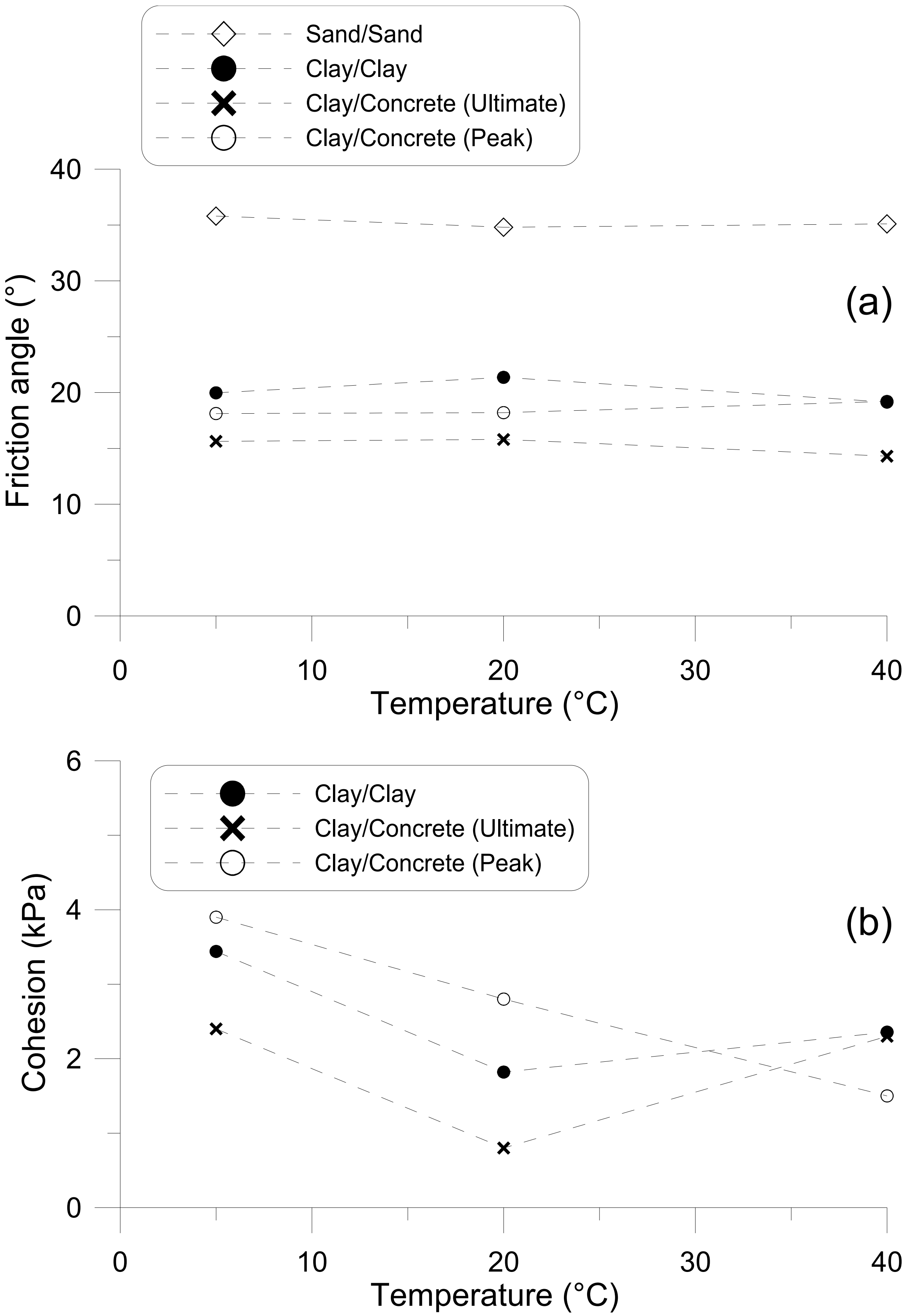

Figure 12. Effect of temperature on (a) friction angle and (b) cohesion

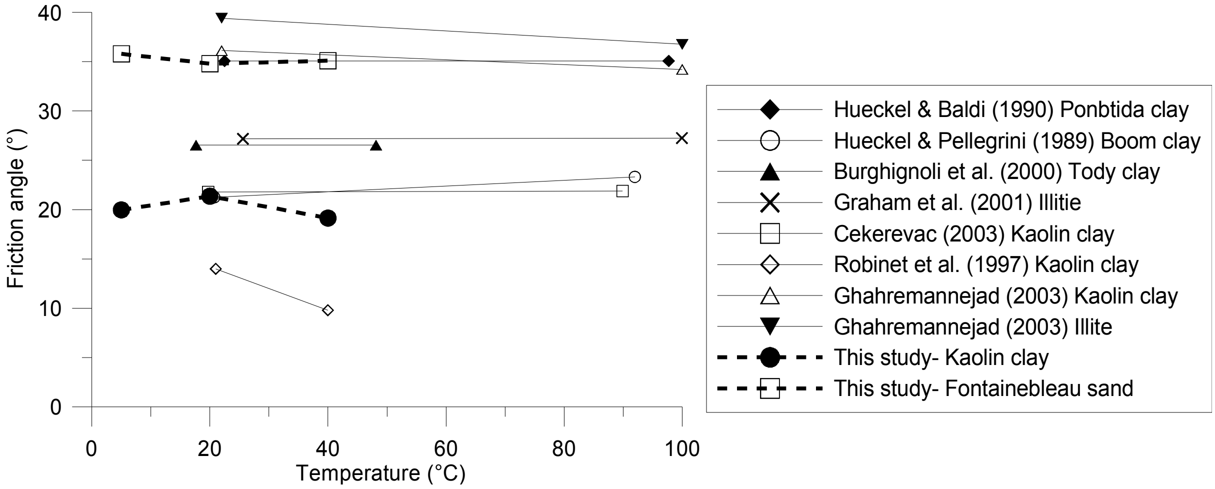

Figure 13. Effect of temperature on friction angle