Temperature Effects on Unconfined Compressive Strength of Clay Soils: Experimental and Constitutive Study

Fariborz Mohammadi  
Tehran University: University of Tehran

Soheib Maghsoodi  
TU Delft: Technische Universiteit Delft

Akbar Cheshomi (✉ a.cheshomi@ut.ac.ir)  
Tehran University: University of Tehran  https://orcid.org/0000-0002-0024-6161

Ali Mohammad Rajabi  
Tehran University: University of Tehran

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Temperature effects on unconfined compressive strength of clay soils: Experimental and constitutive study

Fariborz Mohammadi 1; Soheib Maghsoodi 2; Akbar Cheshomi 1; Ali M. Rajabi 1

1 College of Science, School of Geology, University of Tehran, Tehran, Iran
2 Geo-Engineering Section, Faculty of Civil Engineering and Geoscience, Delft University of Technology, Delft, the Netherlands

Corresponding author: Akbar Cheshomi (email: a.cheshomi@ut.ac.ir)

Abstract: Unconfined compressive strength ($S_u$) is one of the soil engineering parameters used in geotechnical designs. Due to the temperature changes caused by some human activities, it is important to study the changes in $S_u$ at different temperatures. For this purpose, kaolin, illite and montmorillonite clays with a liquid limit (LL) of 47, 80 and 119 respectively, were tested in a temperature-controlled cell in temperature range of 20 to 60 °C. The results showed that the pore water pressure is a function of temperature and by heating, pore water pressure in the samples increased. In all three types of clay, the $S_u$ decreased linearly with increasing temperature. The reduction of $S_u$ in kaolin is more than illite and in illite is more than montmorillonite. The reason for this reduction, might be due the difference in the mineralogy of the clays. The results of unconfined compressive tests at different temperatures were simulated using hypoplastic model.

Keywords: temperature; unconfined compressive strength ($S_u$); clays; pore water pressure; hypoplastic model

1 Introduction

Human activities, such as disposal of high-level radioactive nuclear wastes, geothermal heat storage, energy geostuctures (piles, walls and slabs) and buried high voltage cables, disturb the temperature equilibrium of ground (Brandon et al. 1989; Ghorbani et al. 2020; Lahoori 2020; Lahoori et al. 2021; Maghsoodi 2020; Maghsoodi et al. 2021; Menaceur et al. 2021; Motamedi et al. 2021; Murphy et al. 2015; Tourchi et al. 2021). The temperature disturbance may impact the soil physico-mechanical parameters such as shear strength, volumetric behaviour and pore water pressure. Among the mentioned mechanical properties unconfined compressive strength ($S_u$) of soil is of great importance due to its application in engineering practice. Theoretically, for saturated clays the unconfined shear strength and unconsolidated undrained (UU) tests should lead to the same $S_u$ but the unconfined compressive strength is slightly lower than UU tests in practice (Das 2019).

Effect of temperature on mechanical response of clays depends on the heating phase (drained or undrained), stress history (normally consolidated or overconsolidated), clay characteristics (activity, plasticity index, ...) and shearing type (drained or undrained, monotonic or cyclic)
Some studies have observed an increase in shear strength, some other reported a decrease while some have indicated an independence to temperature variations (Abuel-Naga, Bergado and Lim 2007; Cekerevac and Laloui 2004; Kuntiwattanakul et al. 1995). The uncertainties regarding the impact of temperature on shear strength of clays necessitate more soil element tests under different stress paths (drained and undrained triaxial, unconfined, direct shear).

Undrained heating of normally consolidated clay increases the pore water pressure and this increase continues with keeping the higher temperature constant (Burghignoli et al. 2000). With subsequent cooling the pore pressure decreases. In overconsolidated clays, undrained heating causes excess pore water pressure (PWP) generation but by keeping the higher temperature constant PWP tends to decrease (Burghignoli et al. 2000; Ghaaowd et al. 2015; Abuel-Naga, Bergado and Bouazza 2007; Graham et al. 2001; Monfared et al. 2011; Monfared et al. 2014). In drained heating, normally consolidated clays tend to contract which is irreversible in subsequent cooling, while for highly overconsolidated clays dilates upon heating. This dilation is reversible with cooling (Cekerevac and Laloui 2004; Baldi et al. 1988).

In drained shearing, with increasing temperature, normally consolidated clay contracts and shear strength increases. Cekerevac and Laloui 2004 investigated the effect of temperature on the mechanical behaviour of kaolin under drained conditions and the shear strength of NC kaolin clay increased after heating. The same observation has been reported by several authors for NC clays (cite abuel naga and some others). On the other hand, in highly overconsolidated clays, different results have been reported in the literature. Some of these studies indicate that the shear stress tends to decrease upon heating (Hueckel and Baldi 1990). They explained this behaviour by the ductile behaviour of the clay during heating. On the contrary Abuel-Naga, Bergado and Lim 2007 by testing soft Bangkok clay at different temperatures, reported an increase in shear strength of highly OC clays while the shear stress of kaolin clay with an OCR=12 at 20 and 90°C were almost the same (Cekerevac and Laloui 2004).

In undrained shearing, Kuntiwattanakul et al. 1995 investigated the effect of temperature on the shear strength of kaolin and they observed that with increasing temperature in NC clay, shear strength increased but in OC clay with increasing temperature, the shear strength remain unchanged. Hueckel and Pellegrini 1992 investigated effect of heating and cooling cycles on the undrained shear strength of Boom clay and Pontida clay. They concluded that increasing the temperature causes large irreversible strains in the sample.

Extensive research has been carried out to clarify the impact of temperature on friction angle or critical state coefficient (M) of soils. Among these works, Mitchell et al. 2005 reported that, thermal loads would change the interparticle forces, cohesion and/or friction angle of the soil. On the other hand, Hueckel and Borsetto 1990; Houston and Lin 1987; Graham et al. 2001 and Cekerevac and Laloui 2004 showed that the strength envelope was independent of temperature variations. Hueckel et al. 2009 have explained that the variation of friction angle with temperature may be due to the physico-chemical interactions of clay particles. The thickness of adsorbed water may vary with temperature which changes the contacts between...
particles. De Bruyn and Thimus 1996 showed with testing Boom-clay at different temperatures and different confining pressures, with heating the soil friction angle decreased. On the other hand, they also observed that the soil cohesion increased with temperature increase while Yu et al. 2018 reported a decrease in cohesion with heating and they also reported that the effect of temperature on the friction angle is not clear.

Regarding the unconfined compression strength, Sherif and Burrous 1969; Laguros 1969; Murayama 1969; Noble and Demirel 1969 carried out UCS tests on Osaka clay, kaolin, illite and Montmorionite clay samples in temperature ranges of 20 to 70 °C. They all concluded that with undrained heating, the unconfined compressive strength of clay samples decreased. The reduction of shear strength under heating could be related to the increase in pore water pressure and decrease in effective stress. Sherif and Burrous 1969 mentioned also that the adsorbed water layer around the particles experienced a less rigid state when temperature raised which could be one of the reasons of the strength reduction.

Among different methods to investigate the shear strength of soils, direct shear test is used extensively in the literature (Vasilescu et al. 2019; Di Donna et al. 2015; Yin 2021; Vafaei et al. 2021; Yazdani et al. 2019 and Xiao et al. 2014). Maghsoodi et al. 2020b used direct shear test to investigate effect of temperature changes on sand and clay shear strength. Direct shear tests were performed on Fontainebleau sand and kaolin clay. They concluded that the impact of temperature on sandy soil was negligible and the sand behaved thermo-elastic. However, increasing the temperature (22 to 60 °C) in the kaolin clay increased the cohesion and consequently increased the shear strength.

Several constitutive models are proposed to take into account the effect of temperature on mechanical behaviour of soils (Hueckel and Borsetto 1990; Graham et al. 2001; Hueckel et al. 2009; Lalou and François 2009; Hamidi and Khazaie 2010; Yao and Zhou 2013; Mašín and Khalili 2012). Some of these models are based on elasto-plastic approach and some are developed based on hypoplasticity. In recent years capacity and limitation of these models have been extensively discussed in the literature (Hájek et al. 2009; Wichtmann et al. 2019). Among these models, hypoplastic model, has been extensively used in the literature due to its capacity in good simulation of element tests and boundary value problems and also limited number of parameters (Staubach, Machaček and Wichtmann 2021; Staubach, Machaček, Sharif and Wichtmann 2021).

According to the previous studies, several research has been carried out on the effect of temperature on soil engineering characteristics and different results have been reported. Due to the variety of methods and materials selected, the results obtained from the research have been different. In this regard, in the present study in order to investigate the effect of temperature change and soil type on unconfined compressive strength ($S_u$), three type of clay with different mineralogy were tested at different temperatures and their $S_u$ was determined. For this purpose, a device with the ability to change and keep the temperature constant during the test was designed and manufactured. Afterwards a hypoplastic model was used to reproduce the experimental results by taking into account the impact of temperature.
2 Experimental approach

2.1 Device description

In order to investigate the effect of temperature on unconfined compressive strength \( (S_u) \) of kaolin, illite and montmorillonite, an apparatus was designed and manufactured. Fig. 1 shows the schematic of the apparatus and its various sections.

To raise the temperature in the sample, a Plexiglas cell with high coefficient of thermal resistance was used. The transparency of this cell allows the sample to be seen during the test and how it deforms at different temperatures. The soil sample was placed in the middle of the cell and then the cell was filled with water. Using a circular element located at the bottom of the cell, the water inside the cell was heated to the desired temperature. Temperature was controlled by a thermocouple at the top of the cell. The element set and the thermocouple were connected to a commanding device which displayed and imposed temperature with an accuracy of 0.1 ℃. By setting the commanding device to the target temperature, the system could reach the temperature with the imposed rate and kept it constant. To apply the axial strain, a loading frame was used which applied the deformation with a rate of 1 mm/min. To measure the axial force a load cell with measuring capacity of 25 kg force and accuracy of 1 gram force was used. This cell allowed to measure the force loaded on the soil sample. To measure the displacement a LVDT with accuracy of 0.01 mm was used. Data acquisition and display section included a data-logger that recorded and displayed the force measured by load cell and the displacement measured by LVDT. Using the data-logger, it was possible to continuously record force-displacement changes over the time during the test. Pore water pressure measurement section consisted of a digital barometer with an accuracy of 0.01 kPa to measure the pore water pressure of the sample. Thermal calibration was performed on all parts of the device in order to avoid any device related deformation with heating.

2.2 Soil properties

To investigate the effect of clay type and temperature changes, three clay samples (kaolin, illite and montmorillonite) were selected. Fig. 2 shows the particle size distribution curve of the clays determined according to the standard ASTM et al. 2007 by hydrometric testing. The Atterberg limits and the specific gravity (GS) of the samples were determined according to the standard ASTM 2005 and ASTM et al. 2010 respectively. The activity of the clays based on the method proposed by Skempton 1953 are presented in Table 1.

Table 2 shows the abundance of minerals in the three clay samples based on XRD analysis. In kaolin, about 60% of the mineralogical composition of the sample is kaolinite. The second sample contains about 51% of illite mineral. In the third sample, montmorillonite mineral with 40% abundance is the highest mineral constituent of the sample. Comparing Tables 1 and 2, it can be seen that the difference in the mineralogical composition of the three selected samples has caused differences in the liquid limit (LL), plastic limit (PL) and activity (A) of the samples. So that these three variables have the highest value for montmorillonite sample and the lowest value for kaolin sample. The above variables for the sample contain illite is between the other
two samples.

2.3 Experimental programme and sample preparation

In this study, unconfined compressive strength of kaolin, illite and montmorillonite samples at different temperatures (20, 30, 40, 50 and 60 °C) were determined based on ASTM et al. 2007. The flowchart of the preparation of soil samples and steps of the test that has been conducted are shown in Fig. 3.

To prepare standard sample (length twice the diameter) and to saturate the samples before the test, a cylindrical mold was made that consisted of two cylinders. The small cylinder contained the clay slurry with two porous stone and the large cylinder had a retaining role. To prepare the samples, the dry powder of sample was mixed with distilled water. The amount of distilled water added to the dry powder of the sample was one and half time the liquid limit \((1.5 \times \text{LL})\). After stirring the sample and creating a homogeneous slurry, it was poured into the cylindrical sampler. At the top and bottom of the sample two porous stones were placed and then the sample was consolidated under a vertical stress of 150 kPa which was applied in different increments and was kept for 24 hours.

The vertical stress of 150 kPa was selected based on the dimensions of the sampler, the volume of the sample poured into the sampler, sample consistency and the final desired void ratio of the sample after consolidation. At the end of consolidation phase, based on the dimensions and weight of the sample, the void ratio and degree of saturation of the sample were calculated, which is presented in Table 3. The sample was removed from the sampler using a jack and then a rubber membrane was installed on the sample. In order to reach the desired temperature, the cell was filled with water, therefore the rubber membrane prevented direct contact between the sample and the surrounding water. The sample was then placed inside the cell and then the cell was filled with water. The water inside the cell was heated by the element and the desired temperature was reached using the temperature-control system. Details of the sample preparation process are shown in Fig 3.

During the heating phase, the upper drainage of the cell was closed and the bottom drainage of sample was connected to the barometer, so the sample was heated in undrained conditions. The heating rate was 5 °C/h.

To ensure uniform heating of the sample, according to the suggestion of Chen et al. 2017, the final temperature was kept constant for 2 hours and then the axial load was applied in undrained conditions and the amount of force and displacement was recorded by the data logger. The confining pressure was equal to zero and by applying the axial load (1 mm/min) the sample was sheared in undrained conditions.

3 Modeling approach

In this study the hypoplastic model for clays by Mašín 2005 was used to simulate the experimental results. This model has been thoroughly used and discussed in the literature therefore for the sake brevity just some important equations are presented in the appendix. For further
readings reader are referred to Mašín 2013; Mašín 2014; Niemunis 2003 and Gudehus et al. 2008.

The general rate formulation of hypoplastic follows:

\[ \sigma = f_s(L : \dot{\varepsilon} + f_d N ||\dot{\varepsilon}||) \] (1)

where \( \sigma \) and \( \dot{\varepsilon} \) are the objective stress rate and the Euler stretching tensor, respectively. \( L \) and \( N \) are the fourth- and second-order constitutive tensors, \( f_s \) and \( f_d \) are two scalar factors.

The model has five parameters to be calibrated, \( \phi_c, \lambda, \kappa, N \) and \( \nu \) which have similar (but not the same) interpretation as Modified Cam-clay model parameters. \( \phi_c \) is the critical friction angle of the soil. The slope of the isotropic normal compression line (NCL) in the plane \( \ln(1+e) \) vs. \( \ln p \); \( \kappa \) is the slope of unloading in the same plane. \( N \) is the initial value of \( \ln(1+e) \) at the isotropic normal compression line for \( p = p_r = 1 \) kPa; and finally the parameter \( \nu \) controls the shear stiffness. These parameters can be observed in Fig. 12.

The implemented hypoplastic model for clays in Brinkgreve and Vermeer 1999 was used to simulate the clay behaviour under uniaxial loading. As has been mentioned by Mašín and Khalili 2012 several parameters of the original hypoplastic model was influenced by temperature variations. In this study in order to calibrate the model for different temperatures trial and error calibration was performed to determine the main parameter which is influenced by the temperature. Among different parameters of the model, by solely changing \( N \), and keeping other parameters constant, the temperature impact could be simulated. This simple calibration allows to reproduce clay behaviour at different temperatures by only changing one parameter. Mašín and Khalili 2012 proposed the following the equation to consider the impact of temperature on \( N \):

\[ \ln(1+e) = N(T) - \lambda^*(T) \frac{P}{P_r} \] (2)

\[ N(T) = N + n_T \ln \left( \frac{T}{T_0} \right) \] (3)

where \( T_0 \) is the reference temperature and in this study is considered to be 20°C.

4 Result and Discussion

4.1 Consolidation and heating

In the sample preparation step, a vertical stress of 150 kPa was applied to the samples for 24 hours in order to reach the desired void ratio (see Table 3). For kaolin clay, the before consolidation water content \( (\omega) \) was 70% with a void ratio \( (e) \) of 1.8. These values reduced to \( \omega=41\% \) and \( e=1.1 \) after consolidation. For illite the water content and void ratio before and after consolidation were 96% and 63%, 2.4 and 1.6. For montmorillonite initial water content was 143% which decreased to 91% after consolidation and the void ratios were 3.1 and 1.9 for before and after consolidation. Fig. 4 shows the settlement of the samples versus time. In Fig. 4b-d, the time for 100% of consolidation \( (t_{100}) \) was calculated for kaolin, illite and montmorillonite based
on the method that have been proposed by Gibson and Henkel 1954. After the determination of the $t_{100}$ s using the following equation the total time of shearing can be calculated. This equation lead to shearing rates related to drained conditions therefore rates below the drained conditions can ensure undrained shearing in the samples.

$$t_f = 12.7 \times (t_{100})$$ (4)

The final shearing time in drained conditions for kaolin, illite and montmorillonite was 89, 331 and 368 minutes. With a shearing rate of 1 mm/min (total shearing time of 27 mins), the undrained shearing conditions is ensured.

At the beginning of loading, settlement value for three clay samples is large. For kaolin, the slope of the settlement-time curve was high at the beginning and most of the settlement reached after 2 hours from the start of loading (120 mins). This time is about 20 hours for montmorillonite and illite (1200 mins). The slope of the settlement-time curves shows that under 150 kPa stress, all three specimens reached their fully consolidation state after 24 hours. Due to the same conditions for all three clays, the difference observed in Fig. 4 could be due to the difference in the type of clay mineral and the permeability of the clays. The slow rate of water drainage in illite and montmorillonite can be attributed to the presence of potassium ions in the illite mineral and the presence of water between the layers of montmorillonite mineral. Therefore, the permeability in these two samples was less than the kaolin, so the deformation caused by the application of vertical stress in these two samples occurred at a lower rate than kaolin. Higher permeability of kaolin than illite and illite than montmorillonite has already been reported in literature (Kobayashi et al. 2017; Mesri and Olson 1971).

In undrained heating, with increasing temperature, pore water pressure was generated in all three clays. The generation of pore water pressure with increasing temperature was due to different reactions of water and solid skeleton to temperature variations (Burghignoli et al. 2000). Campanella and Mitchell 1968; Agar et al. 1986 and Aversa and Evangelista 1993 showed that under constant confining pressure, the thermally induced pore water pressure corresponds to dilation or contraction of the solid skeleton and the pore water and also the volumetric stiffness of the solid skeleton.

The pore water pressure at 20°C (room temperature) was equal to zero. Then, with every 5°C of heating, the increase in pore water pressure was recorded. Fig. 5 shows that for all three types of clays with increasing temperature, the pore water pressure increased from zero to 4, 5 and 5 kPa for kaolin, illite and montmorillonite. The increase continued until the temperature of about 50 °C and then the rate of increase with temperature was slow down. The slope of the pore water pressure versus temperature was different before and after 50 °C. This slope was higher for temperatures below 50 °C and lower for temperatures above 50 °C.

With a heating rate of 5 °C/h, each heating increment would take 2 hours. Fig. 6 shows the pore water pressure during heating phase for the three types of clay. The curves indicate that in the heating process, the higher the temperature, the higher the pore water pressure generated in the sample. In addition, the pore water pressure in the samples reaches a stable state after 2 hours. A similar observation has been reported by Wang et al. 2020. For kaolin clay the pore
water pressure at 30, 40, 50 and 60°C were 0.9 kPa, 2.46, 3.55 and 4.1 kPa. For illite, each 10°C (from 20 to 60°C) of heating generated 1.12, 2.88, 4.47 and 5.1 kPa of pore water pressure. For montmorillonite, the same trend as illite was observed (1.33, 3.30, 4.71 and 5.22 kPa at 30, 40, 50 and 60°C). The increase of pore water pressure between 50 to 60 °C in all three clays was lower than other increments. It should be noted that in the process of heating at a certain temperature, the pore water pressure created in illite and montmorillonite is very close to each other and more than kaolin.

4.2 Unconfined compressive strength at different temperatures

Prepared and saturated samples according to the method mentioned in the previous section were tested in undrained conditions. Stress-strain curves for kaolin, illite and montmorillonite at 20, 40 and 60 °C are shown in Fig 7a, b and c.

Comparing figures 7a, b and c, it can be seen that for different clays, the stress-strain curves are different in terms of shape and the maximum stress value. The shape of the curves indicates the behaviour of the samples at different temperatures and their maximum point indicates the final strength of each sample. At each temperature, several tests were performed and the results were almost similar. For the sake of clarity in the figures repeatability tests at one temperature for each sample is presented.

The stress-strain curve of kaolin was different from illite and montmorillonite. kaolin curve showed a gradual increase with increasing the axial strain and the rate of shear axial stress decreased after almost 20%. A clear peak was not observed in the stress-strain curve of kaolin. The initial slope of the stress-strain curve in illite and montmorillonite is higher than that of kaolin, and these samples reach their maximum strength at a lower strain level than the kaolin sample after 10% of axial strain they reached a constant stress level therefore the tests were stopped. The peak stress is visible in the curves of illite and montmorillonite.

The initial slope of stress-strain curve for the illite are greater than for montmorillonite and kaolin. While the difference depends on the mineralogical composition of the clays, but according to the LL and water content (ω) in the samples, the difference in behaviour is justified. In the kaolin sample, ω=41% and LL=47, Therefore, ω of the sample is close to LL. In the illite sample ω=63% and LL=80 and in the montmorillonite sample, ω=91% and LL=119. Therefore, there is a difference between ω and the LL in illite and montmorillonite samples. This makes the kaolin sample softer than the other two samples and the slope of its strain-stress curve is less than the other two samples and the maximum point is not seen in its strain-stress curve.

Fig. 9 shows the images of failed samples. In kaolin samples, the samples became jar-shaped during the test, and in cases where the failure surface was formed, its angle with the horizon surface was measured at about 45°. The jar-shaped of the samples is mostly observed at high temperatures. In illite and montmorillonite, unlike kaolin, the jar-shaped was less seen when the samples has been failure, but the angle of the failure surface in them is mostly 45°.

The maximum stress values for all three samples of stress-strain curves for different temperatures are extracted and shown in Table 4. Changes in $S_u$ versus temperature are plotted in Fig. 7. In all three types of clay, $S_u$ decreases linearly with increasing temperature. $S_u$ for kaolin,
illite and montmorillonite decreased from 19.3, 17.4 and 7.1 kPa at 20°C to 12.5, 11.3 and 4 kPa at 60°C. The slope of the $S_u$ reduction with temperature is higher for kaolin and illite than for montmorillonite. The slope of $S_u$ reduction for kaolin, illite and montmorillonite were -0.170, -0.160 and -0.074. This reduction depends on the soil type, mineralogy, activity and void ratio of clays.

### 4.3 Pore water pressure at different temperatures

Figure 10 shows the evolution of pore water pressure during application of axial loading at different temperatures. It can be observed that for kaolin clay the pore water pressure first increased and then decreased. With increasing temperature, the positive pore water pressure diminished and negative pore water pressure increased. For illite and montmorillonite the trend was different. For both clays the pore water pressure increased while shearing. The difference between clays could be attributed to their void ratio after consolidation which was lower in kaolin clay. The lower void ratio in kaolin clay and being in an overconsolidated state, leads to negative pore water pressure. On the contrary for illite and montmorillonite, the void ratios were higher (1.2, 1.6) therefore they were less stiff compare to kaolin clay and the pore pressure increased while application of axial loading.

The changes in pore water pressure in the heating and shearing process could lead to the decrease in $S_u$. This subject is consistent with the results of previous study (Campanella and Mitchell 1968; De Bruyn and Thimus 1996; Yu et al. 2018) conducted on saturated clay.

According to the structure of the three studied clay samples, the bonding factor between the sheets in the kaolin is hydrogen bonding and secondary valence forces between the gibbsite and silica sheets. In illite the presence of potassium ions and in montmorillonite the weak van der Waals forces and water layers between the sheets (Das 2019). The effect of the increasing temperature on these bonding factors between sheets is different and therefore $S_u$ changes with temperature are not the same for the three clays.

### 4.4 Elastic shear modulus

Figure 11 shows the elastic shear modulus for the clays tested at different temperatures. By dividing the axial stress to axial strain in small increments and plot it against axial strain the evolution of elastic shear modulus can be obtained. As can be seen in Fig. 11a the elastic shear modulus for kaolin clay at 20 °C started with 8.5 MPa at 0.1% of axial strain and with a slow rate it decreased to 1.5 MPa at 27% of axial strain. With heating the initial elastic shear modulus decreased. The initial elastic shear modulus at 40 °C was 8.3 MPa and at 60 °C it again decreased to 7.1 MPa. The rate of reduction for tests at 20 °C is slightly higher than tests at 40 and 60 °C.

Figure 11b shows the evolution of elastic shear modulus for illite. As can be observed the initial elastic modulus at 20 °C started with 28.5 MPa at 0.1 % of axial strain and decreased to 2.6 MPa at 13% of axial strain. Heating decreased the initial elastic modulus from 28.5 to 27 to 25 MPa at 20, 40 and 60°C respectively. The rate of reduction for 20 and 60 °C was almost similar.
Elastic shear modulus reduction for montmorillonite can be seen in Fig. 11c. The same trend as other clays was observed in this test but the reduction of initial elastic shear modulus at 60 °C was more significant in montmorillonite. The initial elastic modulus at 20 °C was 15.5 MPa and it reduced to 14 and 5.9 at 40 and 60 °C respectively.

4.5 Modeling results

In order to obtain N, calibration was performed at 20 and 60 °C then by extrapolating the values corresponding to 30, 40, and 50 °C were obtained. The trend of N with LnT/T0 is illustrated in Fig. 13 for the clays. Similar reductive trend of N with LnT/T0 has been reported by Mašín and Khalili 2012.

Using the parameters shown in table 5, the unconfined compressive test for clays at different temperatures was simulated. Fig. 14 illustrates the modelling simulation against experimental results. For all of the simulations, the parameters were calibrated against tests at 20 °C and by changing N the model capacity was examined for the tests at other temperatures (30, 40, 50 and 60 °C). For kaolin clay, the same friction angle (21 °) as Mašín 2013 was selected as input parameter. The other parameters (λ* = 0.055, κ* = 0.0195, N20°C = 0.995, N60°C = 0.970 and ν/r = 0.7) was found by tuning the values proposed by Gudehus et al. 2008 for these clays. it can be observed the initial stiffness reproduced by the model up to an axial strain of 5% was slightly higher than experimental results at 50 and 60 °C but the overall trend and particularly the axial stress at large axial strains (> 10%) of stress-strain curve was well reproduced by the model.

For illite the model parameters were found to be φc = 22°, λ* = 0.075, κ* = 0.0090, N20°C = 1.287, N60°C = 1.248 and ν/r = 0.2. For tests at 30, 40, 50 and 60 °C the peak stress was not replicated by the model but the stress corresponds to larger strains were reproduced correctly by the model (Fig. 14b).

Simulations are in good agreement for montmorillonite results at different temperatures (Fig. 14c). The friction angle in the model was 22 °, λ* was found to be 0.070, κ* was 0.012 and ν/r was equal to 0.3. By decreasing N from 1.310 (20 °C) to 1.270 (60 °C), impact of temperature could be reproduced. The initial stiffness reproduced by the model was slightly lower than experimental results for tests at 20, 30 and 40 °C.

5 Conclusions

In order to investigate the effect of temperature on unconfined compressive strength of clays, a cell with the ability to increase the temperature was considered and experiments in undrained conditions with cell pressure equal zero on three types of clay (illite, kaolin and montmorillonite) under saturated conditions at temperatures of 20, 30, 40, 50 and 60 °C were carried out and afterwards using hypoplastic model for clays, the experimental results were replicated with implementing the impact of temperature in the constitutive formulation. The following remarks can be mentioned:

- With increasing temperature for three soil samples, the unconfined compressive strength de-
creased linearly. The reason for this decrease was the increase of pore water pressure due to heating. Due to the differences in the mineralogical composition of the studied soils, the mentioned reduction was different for different clay soils. Increasing the temperature from 20 to 60 °C reduced the strength by 35, 35 and 43% for kaolin, illite and montmorillonite, respectively.

- Increasing temperature reduced the initial elastic modulus in three types of clay.
- The stress-strain curve of kaolin at different temperatures had no peak, while for illite and montmorillonite samples a clear peak at strains around 2% was observed.
- In the heating phase with a rate of 5°C/h, the pore water pressure in the samples increased. The increase in pore water pressure in illite and montmorillonite was greater than kaolin.
- During the application of axial loading, the pore water pressure in kaolin first slightly increased and then decreased. In illite and montmorillonite, the increase in pore water pressure at the beginning of the axial loading was greater than in kaolin.
- Using single set of parameters for each soil, by taking into account the impact of temperature on the initial void ratio of the samples, the hypoplastic model replicated the experimental results with good agreement.

Further studies should be carried out in order to investigate the undrained shear strength of these clays in triaxial device at different temperatures to compare the results with unconfined tests.
Formulation of the hypoplastic model is as follows (Maˇs´ın 2013):

\[ \dot{\mathbf{T}} = f_s \mathcal{L} : \mathbf{D} f_d \mathcal{A} : \mathbf{d} || \mathbf{D} || \]  

with

\[ \mathcal{L} = \mathcal{I} + \frac{\nu}{1 - 2\nu} \mathbf{1} \otimes \mathbf{1} \]  

\[ \mathcal{A} = f_s \mathcal{L} + \frac{T}{\lambda^*} \otimes \mathbf{1} \]  

\[ f_s = \frac{3p}{2} \left( \frac{1}{\lambda^*} + \frac{1}{\kappa^*} \right) \frac{1 - 2\nu}{1 + \nu} \]  

where \( \nu, \lambda^* \) and \( \kappa^* \) are model parameters, \( p = -\text{tr} \mathbf{T}/3 \), and \( \mathcal{I} \) and \( \mathbf{I} \) are second- and fourth order unity tensors respectively. The factor \( f_d \) reads

\[ f_d = \left( \frac{2p}{p_c} \right)^\alpha \]  

with \( \alpha = 2 \) and the equivalent pressure

\[ p_e = p_r e^{\frac{N - \ln(1 + e)}{\lambda^*}} \]  

where \( N \) is a parameter and \( p_r \) is a reference stress equal to 1 kPa. The factor \( f_d^A \) reads

\[ f_d^A = 2^\alpha (1 - F_m)^{\alpha/\omega} \]  

where \( F_m \) is the Matsuoka–Nakai factor calculated from

\[ F_m = \frac{9I_3 + I_1 I_2}{I_3 + I_1 I_2} \]  

and the exponent \( \omega \) reads

\[ \omega = -\frac{\ln(\cos^2 \phi_c)}{\ln 2} + a(F_m - \sin^2 \phi_c) \]  

\[ I_1 = \text{tr} \mathbf{T} \]  

\[ I_2 = \frac{1}{2} [\mathbf{T} : \mathbf{T} - (I_1)^2] \]  

\[ I_3 = \text{det} \mathbf{T} \]
Finally, the asymptotic strain rate direction $\mathbf{d}$ is calculated as
\[ \mathbf{d} = \frac{\mathbf{d}^A}{||\mathbf{d}^A||} \]  
\[ \mathbf{d} = -\mathbf{T}^* + 1 \left[ \frac{2}{3} - \frac{\cos 3\theta + 1}{4} F_m^{1/4} \right] \left[ \frac{\xi/2}{1 - \sin \phi_c} \right] \]  
with the Lode angle $\theta$
\[ \cos 3\theta = -\sqrt{6} tr(\mathbf{T}^* \cdot \mathbf{T}^* \cdot \mathbf{T}^*) / [\mathbf{T}^* : \mathbf{T}^*]^{3/2} \]
and the stress measure $\mathbf{T}^* = \mathbf{T} / tr \mathbf{T} - 1/3$. The model requires five parameters $\phi_c$, $\lambda$, $\kappa$, $N$ and $\nu$, and state variables $\mathbf{T}$ and void ratio $e$. 
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Table 1: Clay physical characteristics.

|            | PL% | LL% | PI% | A   | G<sub>s</sub> |
|------------|-----|-----|-----|-----|---------------|
| kaolin     | 27  | 47  | 20  | 0.48| 2.64         |
| illite     | 31  | 80  | 49  | 0.82| 2.67         |
| montmorillonite | 33  | 119 | 86  | 1.72| 2.66         |
Table 2: Mineral composition characteristics.

| Clay          | kaolinite | illite | montmorillonite | Quartz | Carbonates | Other |
|---------------|-----------|--------|-----------------|--------|------------|-------|
| kaolin        | 60        | 2      | 4               | 26     | 2          | 6     |
| illite        | 4         | 51     | -               | 22     | 13         | 10    |
| montmorillonite | 3       | 3      | 40              | 12     | 20         | 22    |
Table 3: Water content, unit weight and void ratio of clays. BC: before consolidation, AC: after consolidation.

| Clay          | ω (%) | γ (kN/m³) | e   |
|---------------|-------|-----------|-----|
| kaolin        |       |           |     |
| BC*           | 70    | 15.6      | 1.8 |
| AC**          | 41    | 17.6      | 1.1 |
| illite        |       |           |     |
| BC            | 96    | 14.9      | 2.4 |
| AC            | 63    | 16.4      | 1.6 |
| montmorillonite |     |           |     |
| BC            | 143   | 14.1      | 3.1 |
| AC            | 91    | 15.7      | 1.9 |
Table 4: Evolution of unconfined compressive strength at different temperatures.

| $T$ (°C) | $S_u$ (kPa)-kaolin | $S_u$ (kPa)-illite | $S_u$ (kPa)-montmorillonite |
|---------|-------------------|-------------------|-----------------------------|
| 20      | 19.3              | 17.4              | 7.1                         |
| 30      | 17.4              | 16                | 6.6                         |
| 40      | 16.1              | 13.4              | 5.7                         |
| 50      | 14                | 12.2              | 5.4                         |
| 60      | 12.5              | 11.3              | 4                           |
Table 5: Hypoplastic model parameters used in this study.

| soil        | $\phi_c$ | $\lambda^*$ | $\kappa^*$ | $N_{20^\circ C}$ | $N_{60^\circ C}$ | $\nu/\tau$ |
|-------------|----------|--------------|------------|------------------|------------------|-------------|
| kaolin      | 21       | 0.055        | 0.0195     | 0.995            | 0.970            | 0.7         |
| illite      | 18.7     | 0.075        | 0.009      | 1.287            | 1.248            | 0.2         |
| montmorillonite | 18    | 0.070        | 0.012      | 1.31             | 1.27             | 0.3         |
Figure 1: Schematic of the device and its various components. 
a) 1- Load cell, 2-Strain gauge, 3- Temperature sensor, 4- Sample cell, 
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(a) $y = -0.0224x + 0.996$, kaolin

(b) $y = -0.0354x + 1.28$, illite

(c) $y = -0.0364x + 1.31$, montmorillonite
Figure 14: Hypoplastic simulations against experimental results.