Viscous behaviour of St-Roch-de-l'Achigan clay, Quebec

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Abstract: This paper describes the viscous behaviour of St-Roch-de-l'Achigan clay, a Champlain Sea clay from Quebec, Canada. The general geotechnical profile of the soil deposit was first established with static cone penetration tests, vane tests, and some laboratory tests performed at different depths. For the study of the viscous behaviour of the clay, a special laboratory test program was established for specimens taken at depths from 4.8 to 5.8 m. This program included special incremental loading oedometer tests, constant rate of strain (CRS) oedometer tests performed at different strain rates, isotropic and anisotropic triaxial compression tests, and undrained shear tests. All these tests were performed under a constant temperature, varying from 10 to 50 °C. The test results show that the vertical yield stresses and the entire limit state curve depend on strain rate and temperature. The critical state line is also temperature dependent in the void ratio (e) – log principal effective stress (p') diagram but not in the deviator stress (q) – principal effective stress (p') diagram. The results also show that microstructuring may develop when the temperature is high or the strain rate small.

Key words: viscosity, strain rate, temperature, laboratory tests.

Résumé : L'article décrit le comportement visqueux de l'argile de St-Roch-de-l'Achigan, une argile de la mer Champlain, Québec, Canada. Les caractéristiques générales du dépôt argileux furent d'abord obtenues d'essais au piézocône et au scissomètre, ainsi que par quelques essais de laboratoire réalisés à différentes profondeurs. Pour l'étude du comportement visqueux de l'argile, un programme spécial d'essais de laboratoire a été élaboré sur des échantillons prélevés à une profondeur de 4,8 à 5,8 m. Ce programme comprenait: des essais oedométriques spéciaux à chargement par paliers, des essais de compression oedométrique à vitesse contrôlée (CRS), des essais de compression triaxiale isotrope et anisotrope suivis d'essais de compression triaxiale en conditions non drainées. Tous ces essais étaient réalisés à une température constante pouvant varier entre 10 °C et 50 °C. Les résultats d'essais ont montré que l'état limite en condition de chargement unidimensionnel ainsi que toute la courbe d'état limite dépendent de la vitesse de déformation et de la température. L'état critique dépend aussi de la température dans le plan e – log p' mais pas dans le plan q–p'. Les résultats montrent aussi que la microstructure peut aussi se développer quand la température est élevée ou la vitesse de déformation faible.

Mot clés : viscosité, vitesse de déformation, température, essais de laboratoire.

1. Introduction

The viscous behaviour of clays has been a topic of interest in geotechnical engineering for a long time. The influence of time and strain rate has been discussed in the literature since the works by Buisman (1936) and Taylor (1942), and in 1969 the U.S. Highway Research Board organized a conference on the effects of temperature on the engineering behaviour of soils. Since that time, studies on the effects of strain rate and temperature on compression, strength parameters, critical state, limit state, and permeability were carried out by Mitchell (1964), Campanella (1965), Mitchell et al. (1969), Lowe (1974), Leroueil et al. (1985), Boudali (1995), and others and were summarized by Leroueil and Marques (1996).

Research on the viscous behaviour of soils responds to growing needs in geotechnical engineering: interpretation of tests that are performed at different strain rates and temperatures (Leroueil and Marques 1996); long-term behaviour of clay foundations under embankments (Leroueil 1996); storage of nuclear waste (Hueckel and Peano 1987; Lingnau et al. 1995); deep foundations used as heat exchangers (Laloui et al. 2003); improvement of foundation characteristics by heating (Edil and Fox 1994); and soil deposits used for heat energy storage (Bergenståhl et al. 1994; Moritz 1995).

Experimental studies were performed on both laboratory-reconstituted clays and natural clays. With few exceptions (Boudali et al. 1994; Boudali 1995; Akagi and Komiya

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1995; Marques 1996, 2001), however, most studies were performed on either the effect of strain rate or the effect of temperature. The influence of anisotropy of natural clays and of microstructure was not considered.

The modelling of the viscous behaviour of soils reflects laboratory studies. There are models that deal with the influence of strain rate (e.g., Yin et al. 1994; Rowe and Hinchberger 1998; Kim and Leroueil 2001) and with the effect of temperature (e.g., Hueckel and Baldi 1990; Lingnau et al. 1995; Laloui and Modaressi 1997). If the effects of strain rate and temperature are combined (Boudali et al. 1994), however, there does not appear to be a numerical model that combines both factors.

The present study aims at studying the combined effect of temperature and strain rate on the general behaviour (compression, limit state, strength, critical state, etc.) of natural clay from St-Roch-de-l'Achigan, Quebec, Canada. Interesting information on the influence of strain rate and temperature on the microstructuration of clays was also obtained. Another objective of the study was to obtain data for a comparison between laboratory and field behaviours in the context of a field study on preloading by the combined effect of vacuum and heating (Marques et al. 2000; Marques 2001).

2. General site characteristics

St-Roch-de-l'Achigan is situated in the Province of Quebec, Canada, 30 km north of Montréal. The properties of St-Roch-de-l'Achigan clay, deposited in the Champlain Sea of Eastern Canada, are within the ranges found for Champlain Sea clays by Leroueil et al. (1983) and Leroueil (1997). Hydraulic properties are also very similar to those found by Tanguay et al. (1991) at St-Esprit, about 1 km from the St-Roch-de-l'Achigan site.

Characterization tests, oedometer compression tests with permeability measurements, constant rate of strain (CRS) oedometer tests with controlled temperature, and triaxial isotropic compression tests at 20 °C were carried out on samples collected at depths between 2.5 m and 9 m with the 200 mm diameter Laval sampler (La Rochelle et al. 1981).

The following geotechnical features of the clay deposit are shown as a function of depth in Fig. 1: in situ unit weight ($\gamma_{\mathrm{nat.}}$), grain-size distribution, natural water content ($w_{\mathrm{nat.}}$), liquid and plastic limits (w_{L} and w_{P}), plasticity index (I_{P}), undrained shear strength (S_{u}), vertical yield stress from conventional 24 h oedometer tests (σ'_{pconv}), in situ vertical effective stress (σ'_{v0}), and pore pressure (u_0).

The St-Roch-de-l'Achigan clay deposit consists of a 2.3 m thick weathered clay crust overlying a layer about 10 m thick of sensitive soft to firm silty clay (sensitivity S_{t} from 30 to 50), a till layer, and bedrock. Four piezocone penetration tests showed that, except for the crust, the clay deposit is quite homogeneous.

As shown in Fig. 1, the clay is highly plastic (I_{p} from 41 to 49), with a natural water content linearly decreasing with depth from 92% at 3 m to 75% at 9 m. The undrained shear strength measured by vane tests varies from 69 kPa at a depth of 1.5 m to a minimum value of 18 kPa at 3 m and then increases to 27 kPa at 4.5 m and linearly to 40 kPa at 8 m. This profile is in accordance with that obtained with a Swedish fall cone test, except at 9 m where the latter test gave a higher value than the vane test.

St-Roch-de-l'Achigan clay is slightly overconsolidated, with an overconsolidation ratio (OCR) between 1.8 and 2.4. The initial hydraulic conductivity of the clay is between 1.6 and 3.3×10^{-9} m/s. The compression ratio $C_{\mathrm{c}}/(1 + e_0)$ is between 0.59 and 1.36 (where C_{c} is the compression index and e_0 is the initial void ratio), indicating that the behaviour of this clay may be significantly influenced by viscous phenomena during consolidation processes (Leroueil 1996).

Figure 2 shows yield stresses obtained from different tests: conventional 24 h oedometer tests at a temperature T of 20 °C, CRS tests at 10 °C, isotropic triaxial compression tests, and piezocone tests. The ratio between isotropic and oedometer yield stresses ($\sigma'_{\mathrm{pi}}/\sigma'_{\mathrm{pconv}}$) lies between 0.64 and 0.66, which is typical of Champlain Sea clays (Díaz-Rodriguez et al. 1992). As expected, vertical yield stresses obtained from CRS oedometer tests (σ'_{pCRS}) carried out at 10 °C and a strain rate ($\dot{\varepsilon}_1$) of 2×10^{-6} s^{-1} are 20%–25% higher than those obtained in conventional oedometer tests performed at 20 °C and corresponding to strain rates in the order of 1×10^{-7} s^{-1} (Leroueil 1988, 1996).

Vertical yield stress (σ'_{pcone}) can also be deduced from piezocone penetration tests using the following equation:

$$[1] \qquad N_{\sigma T} = (q_{\mathrm{t}} - \sigma_{\mathrm{v0}})/\sigma'_{\mathrm{pcone}}$$

in which q_{t} is the tip resistance corrected for pore pressure behind the tip (Lunne et al. 1997), and σ_{v0} is the in situ vertical total stress. Good agreement with yield stress values obtained by conventional oedometer tests was obtained when using $N_{\sigma T} = 3.4$, a value suggested by Demers and Leroueil (2002) for Champlain Sea clays. These results confirm that natural clays are anisotropic ($\sigma'_{\mathrm{pi}}/\sigma'_{\mathrm{pconv}}$ significantly smaller than 1.0) and influenced by viscous effects (σ'_{pCRS} (T = 10 °C)/σ'_{pconv} (T = 20 °C) equal to about 1.25).

3. Experimental program

The testing program was defined to investigate the influence of strain rate and temperature on the general behaviour of St-Roch-de-l'Achigan clay. For that purpose, CRS oedometer tests, special oedometer tests, and triaxial tests were performed under constant temperatures varying between 10 and 50 °C. These tests were carried out on samples from depths of 4.8–5.8 m in the middle of the homogeneous clay layer (see Fig. 1), where σ'_{pconv} (T = 20 °C) lies between 120 and 130 kPa (Figs. 1, 2).

CRS compression tests were carried out on 75 mm diameter and 20 mm high specimens at strain rates varying between 10^{-5} and 10^{-7} s^{-1}, and special oedometer tests (IL tests) were carried out on 150 mm diameter and 48 mm high specimens, both under controlled temperatures and with pore-pressure measurement at the bottom of the specimen. In the IL tests, the sample was loaded up to 140 kPa at 10 °C, and after the pore-pressure dissipation the temperature was increased in 48 h steps to 20, 35, and 50 °C.

Isotropic and anisotropic triaxial compression tests were carried out on 37 mm diameter and 71 mm high specimens at 10, 20, and 50 °C. The stress ratios K (= σ'_3/σ'_1, where σ'_1 and σ'_3 are the major and minor principal effective stresses, respectively) used in these tests were equal to 1.0, 0.85, 0.7,

Fig. 1. Geotechnical characteristics of the St-Roch-de-l'Achigan clay deposit.

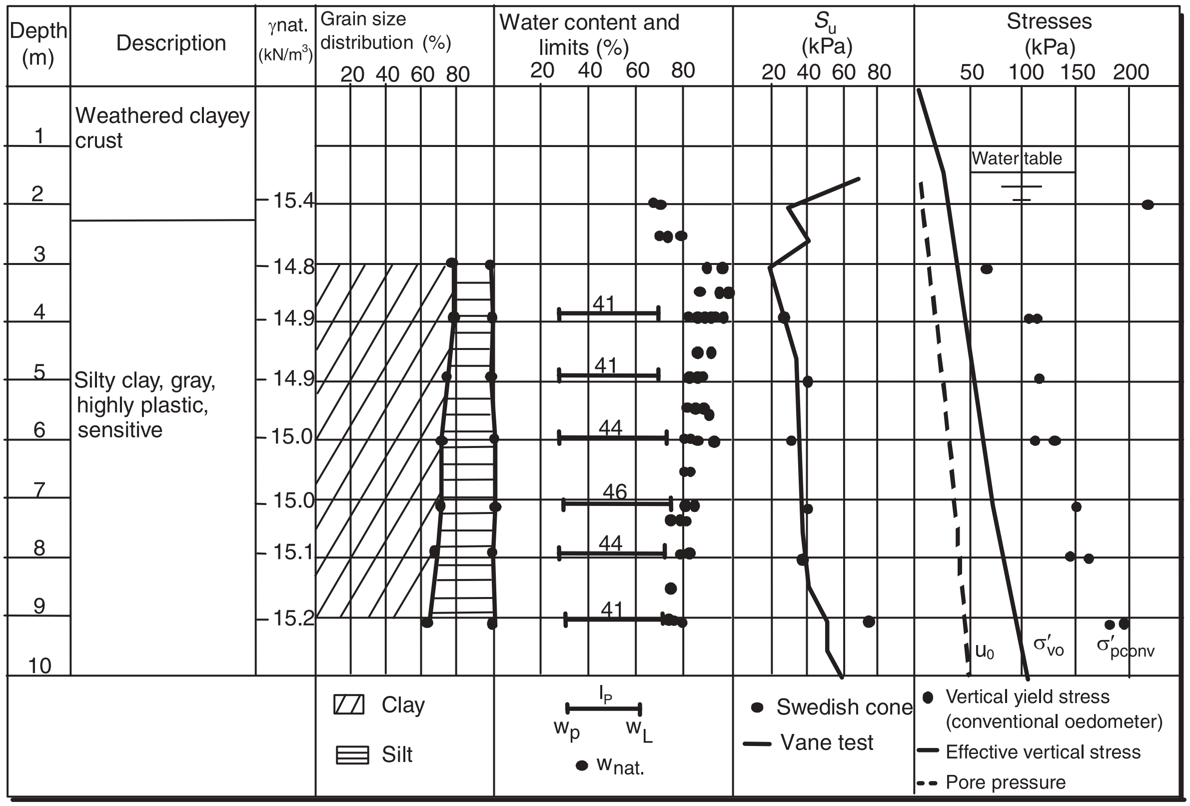
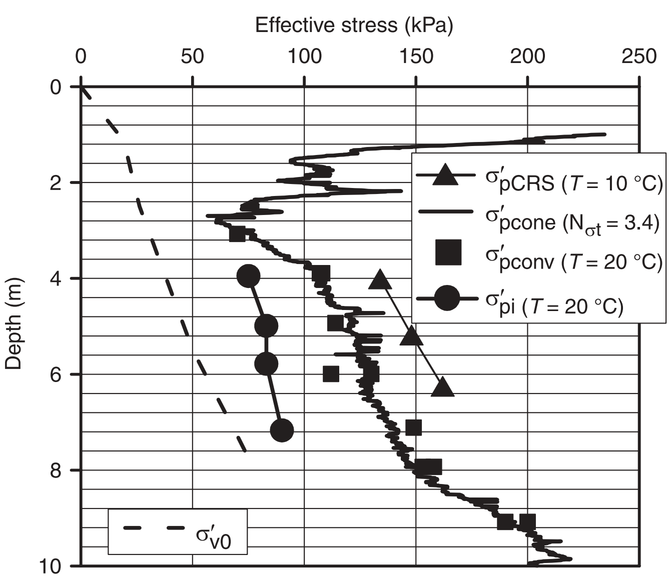


Fig. 2. Variation of vertical yield stresses and in situ vertical effective stress with depth for St-Roch-de-l'Achigan clay.



and 0.5. The stresses were applied in steps, and the compression curves were plotted at a strain rate $\dot{\varepsilon}_1 \approx 2 \times 10^{-7}$ s^{-1}. At the end of some isotropic and anisotropic compression tests, the soil was sheared in undrained compression at an axial strain rate $\dot{\varepsilon}_1 = 1.4 \times 10^{-6}$ s^{-1}. In all tests, a back pressure of 100 kPa was used to ensure full saturation of the soil specimens. The first load was applied at 20 °C to provide a reference for all tests. To increase the temperature from 20 to 50 °C, hot water was pumped through a copper tube placed spirally around the sample installed inside the triaxial cell. For tests carried out at 10 °C, the triaxial equipment was placed inside a cold room, and temperature was decreased from 20 to 10 °C. For all tests the temperature was maintained constant for 24 h before starting or resuming the test.

4. Effects of strain rate and temperature on clay compressibility

Figure 3*a* shows the effect of strain rate on compression curves and pore-pressure (u) variation with vertical effective stress (σ'_v) curves obtained from CRS tests performed at 10 °C. As the strain rate increases, the vertical yield stress also increases and, under a given vertical effective stress, the axial strain (ε_1) decreases. On the other hand, as the temperature increases, the vertical yield stress decreases and, under a given vertical effective stress, the axial strain increases, as shown in Fig. 3*b* for CRS tests carried out at a strain rate of $\dot{\varepsilon}_1 = 10^{-5}$ s^{-1}. This behaviour is similar to that presented by Boudali et al. (1994) for other Champlain Sea clays. Boudali et al. also showed that, when the vertical effective stress is normalized with respect to the vertical yield stress obtained at the testing temperature and strain rate, all the compression curves are on the same normalized compression curve. This is also true for the test results shown in Fig. 3.

Figure 3*b* also shows that under an applied vertical stress of about 10 kPa, the volumetric strain due to heating is about 1.5%; this shows that the slope of the compression curve in the overconsolidated domain is not strongly dependent on temperature, at least between 10 and 50 °C.

Fig. 3. Temperature and strain rate effects on one-dimensional compression and pore-pressure variation with vertical effective stress.

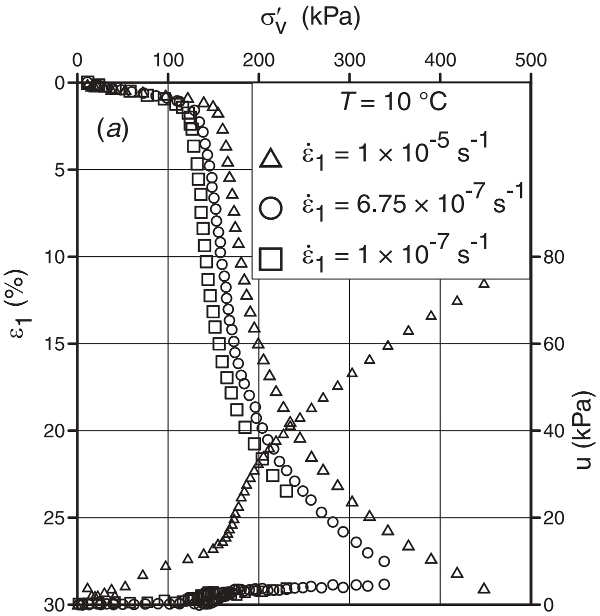


Figure 4 presents the results of a CRS compression test carried out on a single sample at a temperature alternating between 10 and 50 °C. For each step of temperature change the press was stopped and the sample was heated or cooled under drained conditions. The compression test was resumed after 24 h at the same temperature. When the press was turned off, due to incomplete consolidation and soil relaxation, a decrease in total stress was observed, as shown in Fig. 4. It can be seen that the effective stress – strain curve jumps from the 10 °C compression curve to the 50 °C compression curve and vice versa when the temperature is changed, confirming the influence of temperature on clay behaviour.

The influence of both strain rate and temperature on the vertical yield stress (σ_p') is shown in Fig. 5*a*. At a given temperature the relationship between log σ_{pCRS}' and log $\dot{\varepsilon}_1$ is essentially linear, in agreement with the following equation:

$$[2] \qquad \log \sigma_p' = A + (1/m') \log \dot{\varepsilon}_1$$

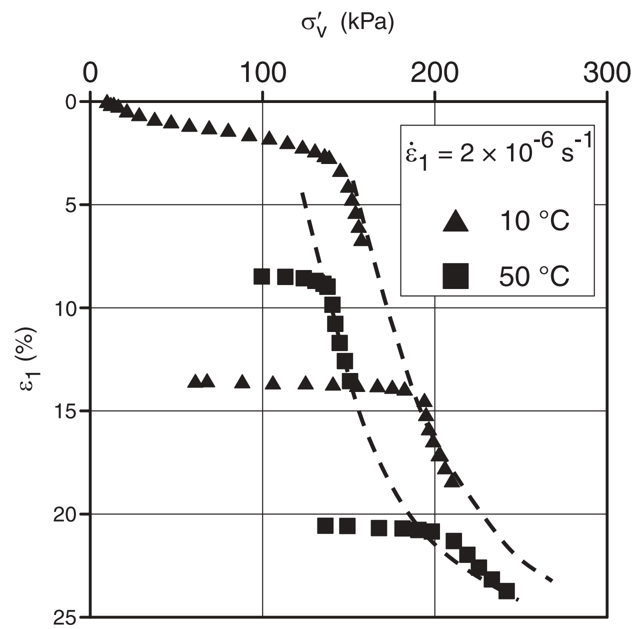
in which A is a temperature-dependent soil parameter, and m' is essentially constant and equal to 16 for the St-Roch-de-l'Achigan clay and a temperature between 10 and 50 °C. This indicates a change in vertical yield stress of 15% per log cycle of strain rate. This m' value is slightly smaller than values generally found for inorganic clays (33–20; Leroueil 1996), indicating a strain-rate effect slightly larger than usual.

Figure 5*b* shows the same vertical yield stresses obtained at different strain rates as a function of temperature. The curves are in relatively good agreement with the following relationship proposed by Moritz (1995):

$$[3] \qquad \sigma_{pT}' = \sigma_{pT_0}' (T_0/T)^{\alpha}$$

in which σ_{pT}' and σ_{pT_0}' are the vertical yield stresses at temperatures T and T_0 (in °C), respectively; and α is a soil parameter. For St-Roch-de-l'Achigan and St-Polycarpe clays (Marques 1996), both Champlain Sea clays, the value of

Fig. 4. Effect of temperature changes on one-dimensional compression.



α is about 0.15, which is also the value proposed by Moritz (1995).

Figure 6 shows the vertical yield stresses normalized with respect to the vertical yield stress at 20 °C for several clays of different geological origins. For some series of tests the $\sigma_{p20°C}'$ value was estimated on average curves, which explains ratios $\sigma_p'/\sigma_{p20\,°C}'$ that can be different from 1 at a temperature of 20 °C. Also considered for some series of tests performed on reconstituted clays were effective vertical stresses taken on virgin compression lines obtained at different temperatures at given void ratios (e). The range of data lies between $\alpha = 0.15$ and $\alpha = 0.1$ (eq. [3]) for temperatures below 20 °C and between $\alpha = 0.15$ and $\alpha = 0.28$ for temper-

Fig. 5. Influence of strain rate and temperature on the vertical yield stress.

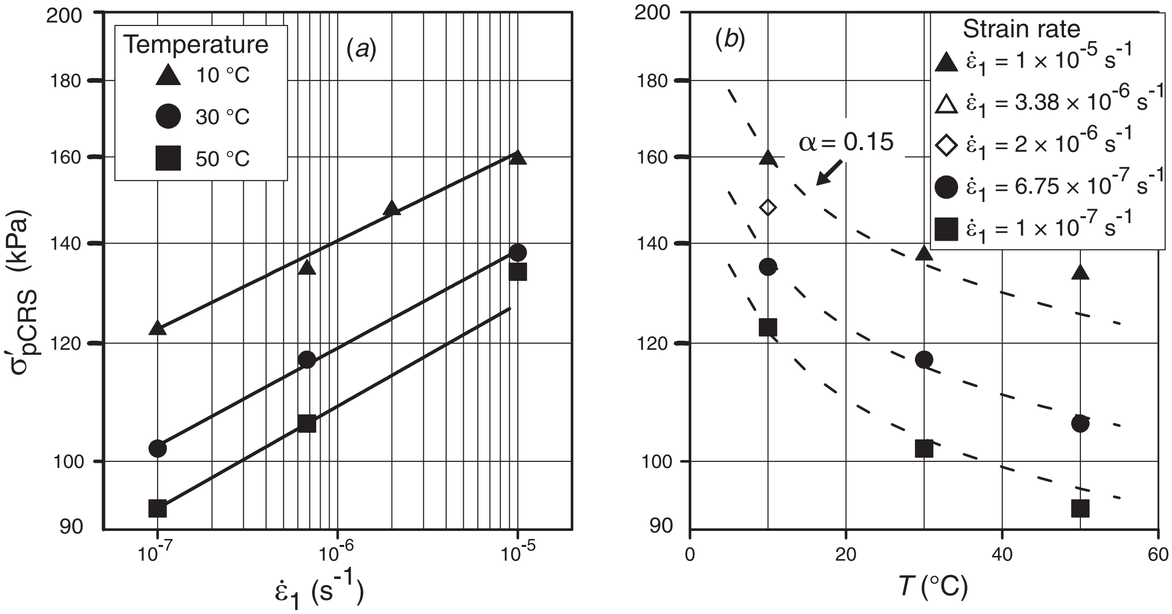
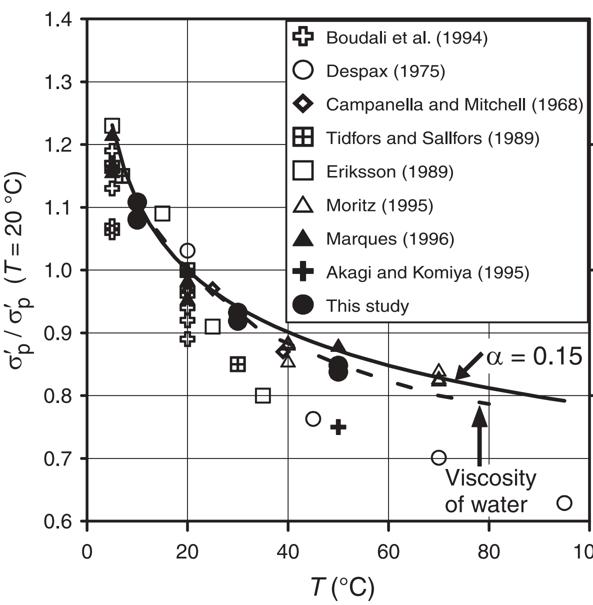


Fig. 6. Normalized viscosity and vertical yield stresses for clays of different origins, as a function of temperature.



atures above 20 °C. This means a larger influence of temperature on vertical yield stress for temperatures below 20 °C. The normalized water viscosity ($\mu_T / \mu_{(T=20\ °C)}$) curve is also shown in Fig. 6, and it is worth noting that the shape of this curve is similar to that of the normalized vertical yield stress curve obtained for $\alpha = 0.15$ (eq. [3]), which could indicate an important influence of water viscosity on the change in vertical yield stress with temperature. For practical purposes, the vertical yield stress typically varies by 1%/°C between 5 and 40 °C, which is quite important.

Figures 3–6 show the influence of strain rate and temperature on the compressibility of the soil skeleton. Temperature also influences characteristics of the pore fluid. When temperature increases, water viscosity decreases and hydraulic conductivity increases. The intrinsic permeability K, defined by the following equation, is constant, however:

$$[4] \qquad K = \frac{k_{T_1} \mu_{T_1}}{\gamma_{T_1}} = \frac{k_{T_2} \mu_{T_2}}{\gamma_{T_2}}$$

in which k_{T_i}, μ_{T_i}, and γ_{T_i} are the hydraulic conductivity, water viscosity, and water density, respectively, at temperature T_i. According to eq. [4], hydraulic conductivity increases by a factor of 2.4 when temperature increases from 10 to 50 °C. This change in hydraulic conductivity could, in particular, explain why in Fig. 3*b* pore pressures generated during the CRS test at 50 °C are much smaller than those generated at 10 °C. The hydraulic conductivity has been back-calculated for these two tests performed at a strain rate $\dot{\varepsilon}_1 = 1 \times 10^{-5}$ s^{-1}, and the results are shown in Fig. 7. Also shown in Fig. 7 are the hydraulic conductivities directly obtained from permeability tests carried out in an oedometer cell at 20 °C. As expected, the results obtained at 20 °C are between those obtained at 10 and 50 °C. The hydraulic conductivity obtained at 50 °C is 2.2 times larger than that obtained at 10 °C, thus confirming the effect of temperature on hydraulic conductivity indicated by eq. [4]. These k versus e curves are essentially linear in the normally consolidated range, with a C_k ($= \Delta e / \Delta \log k$) value equal to 1.

5. Temperature effects on the limit state and the critical state

5.1. Isotropic and anisotropic compression tests

Figure 8 shows isotropic compression curves obtained during the consolidation phase of consolidated, isotropically undrained (CIU) tests carried out at 10, 20, and 50 °C. As expected, and similar to what was observed with the oedometer, yield stress decreases and volumetric deformation ($\Delta V/V_0$) increases when temperature increases. In the overconsolidated range the changes in volumetric strain are small

Fig. 7. Variation of hydraulic conductivity with void ratio and temperature, as deduced from CRS and permeability tests.

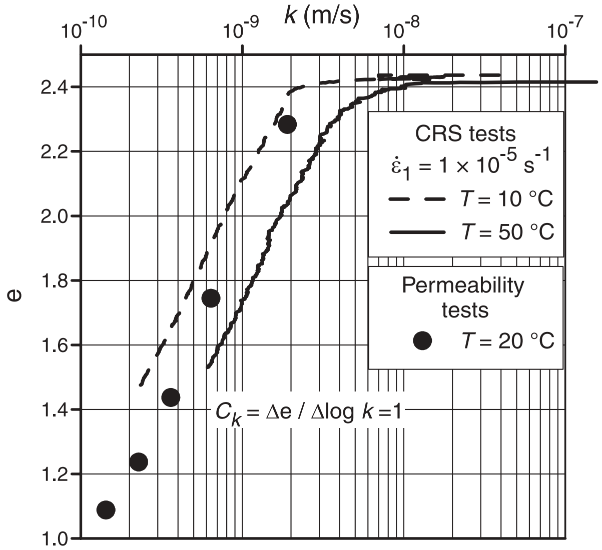
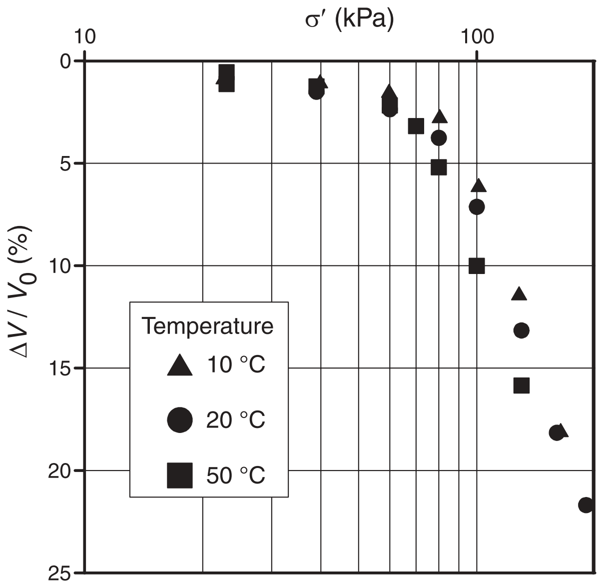


Fig. 8. Isotropic compression curves for triaxial tests at T = 10, 20, and 50 °C.



and indicate a bulk modulus that is not strongly influenced by temperature.

Anisotropic compressions with K (= σ_3'/σ_1') values equal to 0.5, 0.6, 0.7, and 0.85 were also carried out at the same temperatures. Yield stresses are also smaller at higher temperatures, and volumetric deformation increases with an increase in temperature, as shown in Fig. 9*a* for K = 0.7.

Figure 9*b* presents triaxial tests results obtained at different K values at 50 °C in a volumetric strain versus $(\sigma_1' + \sigma_3')/2$ diagram. It can be seen that yield stress and volumetric deformation increase only very slightly when K decreases from 1 to 0.5, which is typical behaviour of natural soft clays (Díaz-Rodriguez et al. 1992).

5.2. CIU tests in the overconsolidated range

Figure 10 shows results of the CIU tests performed after consolidation under an isotropic effective stress (σ_c') of 23 kPa, thus in the overconsolidated range, at temperatures of 10, 20, and 50 °C. The stress–strain (q–ε_1) curves (Fig. 10*a*) are typical of sensitive overconsolidated clays, which present brittle behaviour in shear tests. Peak resistance is at 10 °C and presents about the same value at 20 and 50 °C. As discussed later in the paper, this is possibly due to development of microstructure at 50 °C. Pore pressure increases with an increase in temperature, especially at large deformations (Fig. 10*b*), behaviour also observed by Campanella (1965). The stress paths shown in Fig. 10*c* are very similar initially and then reflect the higher peak strength obtained at 10 °C. At large deformations, stress conditions are on the same strength envelope, but the large deformation strength is also larger at 10 °C than at higher temperatures. The large deformation strength envelope is characterized by a friction angle (ϕ') of 44°, a typical value for Eastern Canada clays in their overconsolidated range (Leroueil 1997). Due to the fact that shear planes are formed during these tests in the overconsolidated range, these large deformation strengths cannot a priori be associated with critical states.

5.3. CIU tests in the normally consolidated range

Figure 11 shows the results of a special CIU test carried out on a specimen consolidated in the normally consolidated range. The specimen was consolidated at 10 °C to an isotropic effective stress of 123 kPa (Fig. 11*a*) and then sheared in undrained conditions up to an axial strain of about 12%. The compression was then stopped and the sample was subjected to undrained heating up to 50 °C before the undrained compression was resumed. At an axial strain of about 16.5%, the compression was stopped. The specimen was cooled to 10 °C in undrained conditions and the undrained compression was resumed up to an axial strain of 25%.

Figure 11*b* shows the variation of deviatoric stress and pore pressure with axial strain, and Fig. 11*c* shows the corresponding stress path. As shown in Fig. 11*c*, the soil reached the critical state strength line before the end of the first stage of loading, at about 12% axial strain (point A_1). After this first stage, heating of the soil from 10 to 50 °C generated an increase in pore pressure and a decrease in deviatoric stress (B_1B_2 in Fig. 11*b*). The opposite held when, at the third stage, the soil was cooled from 50 to 10 °C (C_1C_2 in Fig. 11*b*). As shown in Fig. 11*c*, however, the stress paths B_1B_2 and C_1C_2 essentially remain on the same strength envelope. This behaviour is similar to that shown by Hueckel and Baldi (1990). For conditions close to critical state, s' $(= [\sigma_1' + \sigma_3']/2)$, values decrease when temperature increases, as indicated in Figs. 11*a* and 11*c*.

Stress conditions at the peak obtained from CIU and consolidated, anisotropically undrained (CAU) tests performed at 10, 20, and 50 °C are shown in Fig. 12. An average value of the friction angle at peak on the normally consolidated domain (ϕ'_{peaknc} = 28.5°) is observed, which is well inside the range of ϕ'_{peaknc} values for Champlain Sea clays of between 27 and 30° C (Brousseau 1983). The peak values obtained at 50 °C may be slightly above the average ϕ'_{peaknc} strength envelope. For St-Roch-de-l'Achigan clay, however, if the enve-

Fig. 9. Compression curves for triaxial tests: (*a*) K = 0.7 and different temperatures; (*b*) T = 50 °C and different K values.

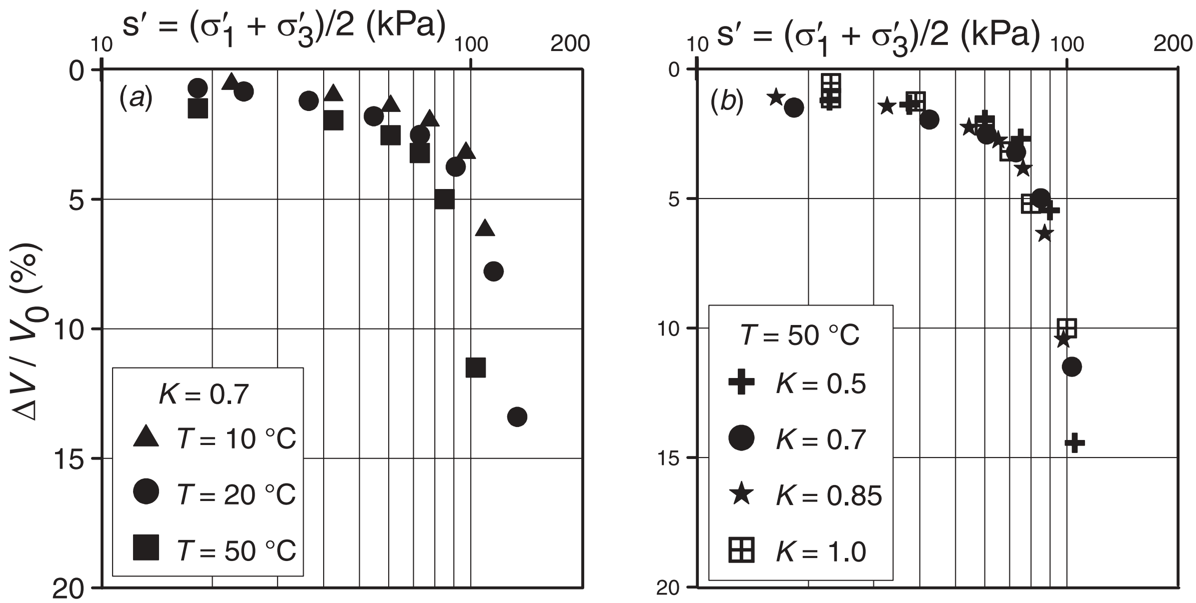


Fig. 10. CIU results in the overconsolidated range (T = 10, 20, and 50 °C): (*a*) stress–strain curves; (*b*) pore pressure – strain curves; (*c*) stress paths.

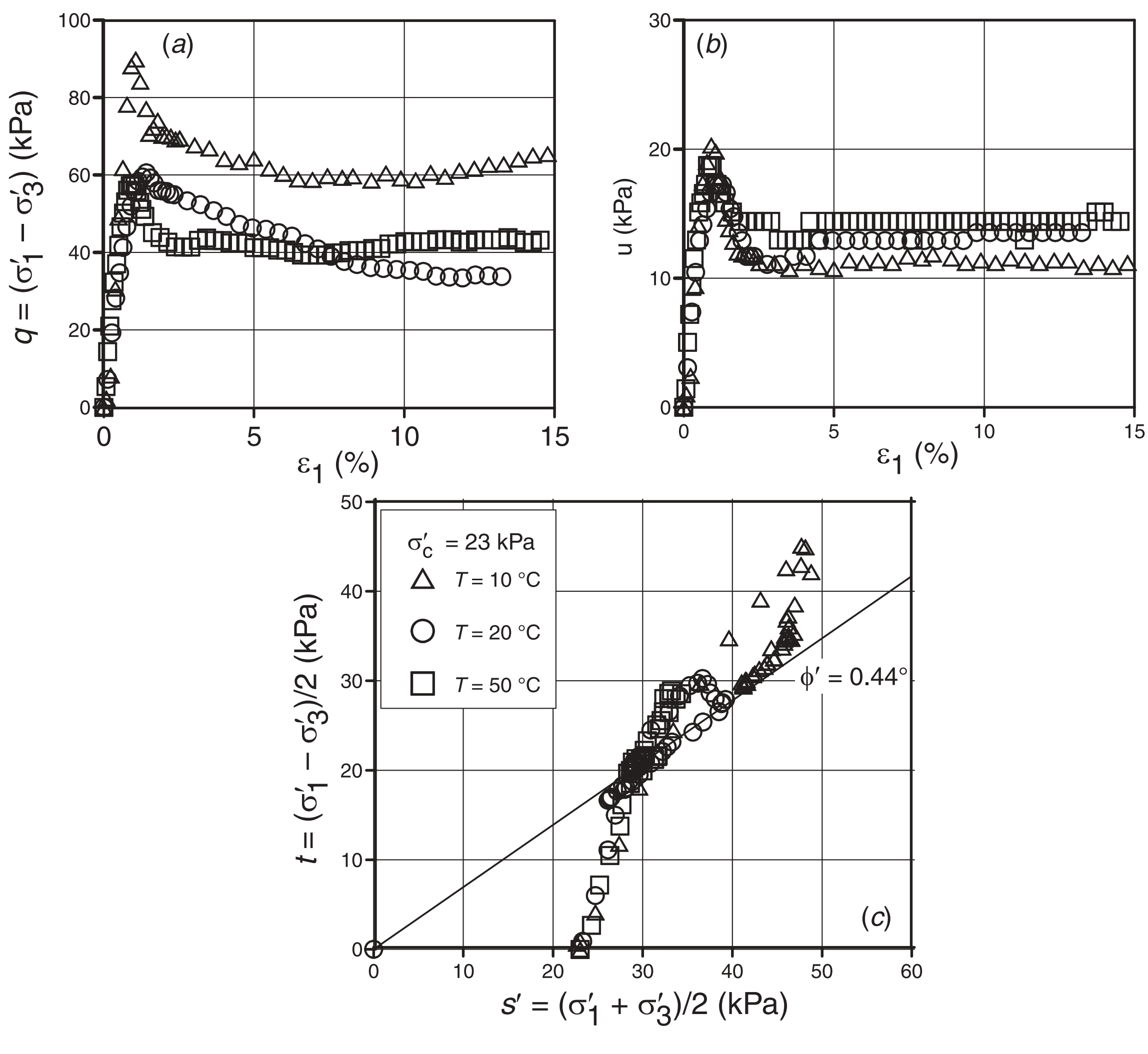


Fig. 11. CIU tests results in the normally consolidated range (T = 10–50 °C): (a) compression curve; (b) stress (q) – strain and pore pressure – strain curves; (c) stress path.

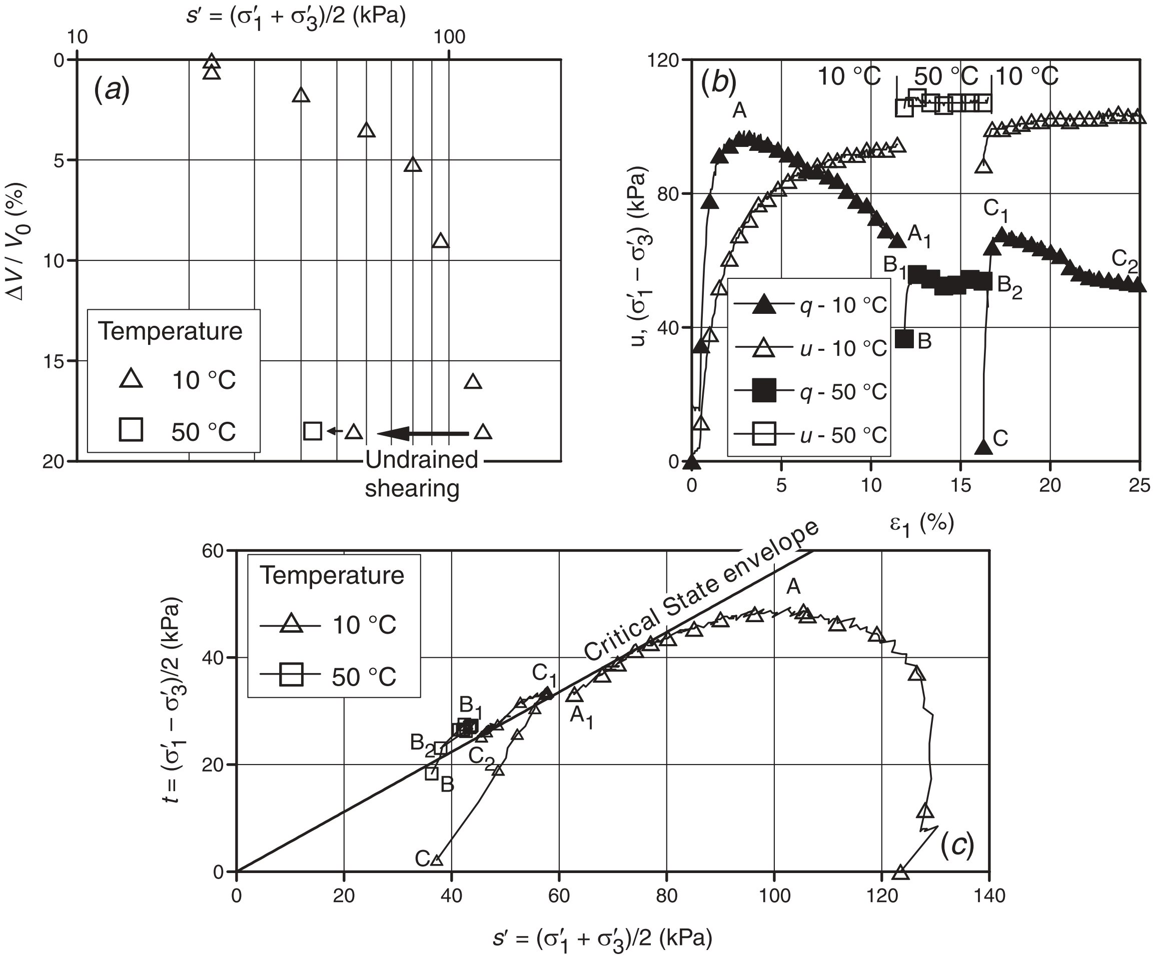
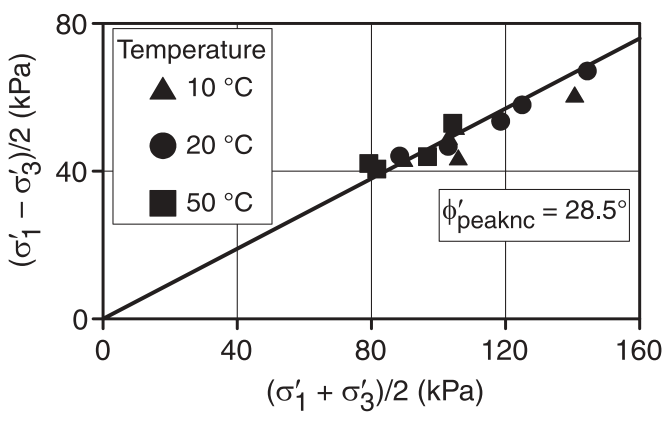


Fig. 12. Stress conditions at the peak in the normally consolidated range.



lope is temperature dependent, the variation is small, which corresponds to other observations reported in the literature (see synthesis in Leroueil and Hight 2002).

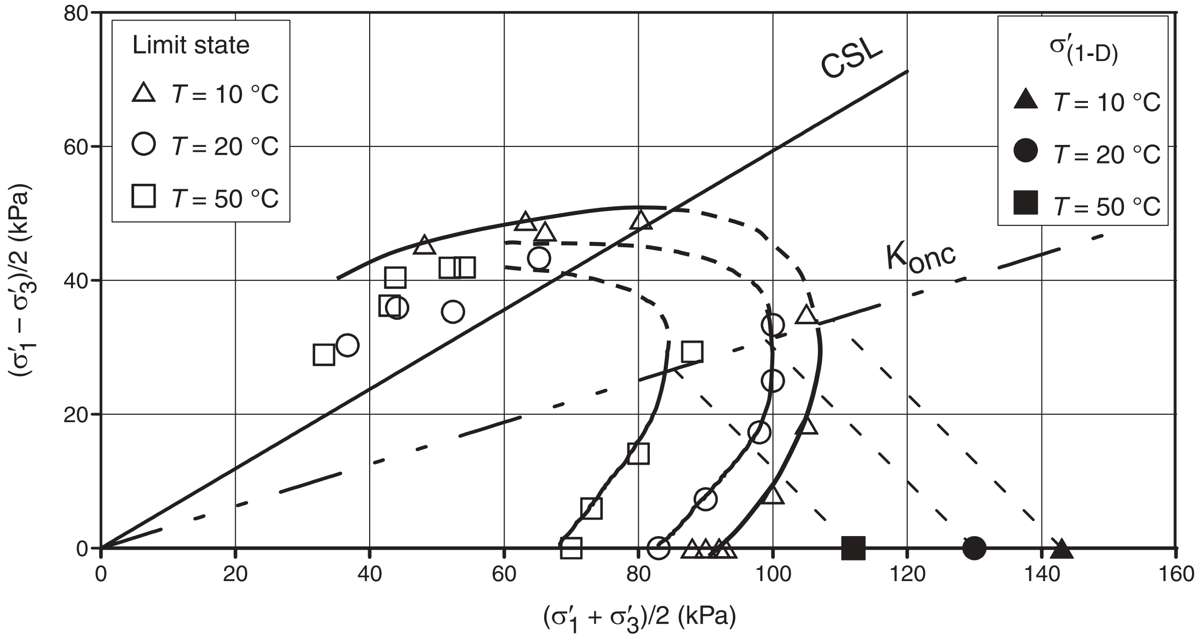
5.4. Limit state curves

CRS oedometer tests carried out under a controlled temperature have shown that yield stresses decrease when temperature increases or strain rate decreases (Moritz 1995; Boudali 1995; Marques 1996). It has also been shown that limit state curves shrink when temperature increases, or when strain rate decreases (Boudali 1995; Leroueil and Marques 1996).

Yield conditions deduced from CIU tests performed in the overconsolidated range, from isotropic and anisotropic triaxial compression tests and from oedometer tests ($\sigma'_{(1-D)}$), with all tests carried out at temperatures of 10, 20 and 50 °C, are shown in Fig. 13 in a $(\sigma_1' - \sigma_3')/2$ versus $(\sigma_1' + \sigma_3')/2$ diagram. The yield stresses were obtained from compression curves (Figs. 8, 9) at a strain rate of about 2×10^{-7} s^{-1}. In the overconsolidated range, peak values were obtained in CIU tests carried out at a strain rate of 1.4×10^{-6} s^{-1}. Since the radial stress was not known at yielding in the oedometer tests, the vertical yield stresses at these temperatures have been plotted on the isotropic axis in Fig. 13. Stress conditions at yielding in one-dimensional compression tests are, however, considered to be close to the K_{0nc} (coefficient of earth pressure at rest at the normally consolidated domain) line ($K_{0nc} = 1 - \sin\phi'_{peaknc} = 0.52$), which is not considered to be affected by temperature. This is confirmed by the similarity between the vertical effective stresses obtained at yielding in the oedometer tests and in the K = constant = 0.5 triaxial anisotropic compression tests (see Fig. 13).

The limit state curves (CSL) obtained at the three temper-

Fig. 13. Influence of temperature on the limit state curve.



atures are shown in Fig. 13. Because the upper part defined from CIU tests and the lower part deduced from compression tests correspond to strain rates that differ by about one order of magnitude, however, these two parts have been joined by broken lines. The limit state curve obtained at 10 °C is well defined. In comparison with this curve, the results obtained at 20 and 50 °C show a shrinking of the limit state curve as temperature increases, even if it is not clear for shear tests. As already indicated, these latter results could possibly be explained by some aging effects on the soil at 50 °C.

5.5. Critical state

CIU and CAU tests performed in the normally consolidated range showed homogeneous conditions of deformation of the specimens, and large strain conditions ($\varepsilon_1 \cong 15\%$) can be associated with critical state conditions. Figure 14 shows the corresponding critical state at 10, 20, and 50 °C. There is some scatter, but all the data are around an average strength envelope that can be characterized by the friction angle at critical state, $\phi'_{CS} = 36.4°$, with little, if any, effect of temperature.

Figure 15 shows the critical state lines (CSL) defined at the three temperatures in a volumetric deformation ($\Delta V/V_0 - p'$) plane. Even though there is some scatter, the critical state lines are essentially parallel. Lingnau et al. (1995) also observed this behaviour at critical state for a sand–bentonite mixture at 26, 65, and 100 °C.

The isotropic compression lines previously shown in Fig. 8 are also plotted in Fig. 15. It appears that the change in p' from one temperature to another is much smaller for the isotropic compression lines than for the critical state lines. The following remarks can be made:

(1) The variation of p' in isotropic compression with temperature can be examined at a volumetric strain $\Delta V/V_0$ of 15%. With reference to p' at 10 °C, there is a decrease of about 6 kPa (4%) at 20 °C and about 21 kPa (14%) at 50 °C. These variations are smaller than the variations in yield stress with temperature observed in oedometer tests (Fig. 5) and in triaxial isotropic and anisotropic compression tests (Figs. 8, 9*a*, 13) which are typically in the order of 30% between 10 and 50 °C. This could possibly be associated with the natural variability of the specimens.

(2) The variation of p' at critical state with temperature can also be examined at a given volumetric strain. For example, at $\Delta V/V_0 = 15\%$ and with reference to p' at 10 °C, the decrease is about 4 kPa (8%) at 20 °C and about 17 kPa (34%) at 50 °C. In this case, the variation is slightly larger than that observed for yield stresses. There is no clear explanation for this variation but, due to the number of specimens considered, it is improbable that it could be due to their natural variability.

6. Viscous behaviour

6.1. Towards a viscous model

It appears from this study that the mechanical behaviour of clays, at yielding and in compression, is influenced by strain rate and temperature, thus by viscosity: preconsolidation pressure decreases with a decrease in strain rate and an increase in temperature (Fig. 5); isotropic yield stress also decreases when temperature increases (Fig. 8); the limit state curve shrinks when temperature increases (Fig. 13) and, at least as a first approximation, the limit state curves obtained at different temperatures can be considered homothetic.

Figure 16 shows the schematic variation of limit state surface with strain rate ($\dot{\varepsilon}_1$) and (or) temperature (T), in the e_0–p'–q space. The limit state is like an "onion," with each peel corresponding to a combination of strain rate and temperature. This general behaviour is in agreement with the test results obtained on St-Roch-de-l'Achigan clay. It is also in agreement with the stress – strain – strain rate – temperature model (σ'_v, ε_v, $\dot{\varepsilon}_v$, T) proposed by Boudali et al. (1994),

Fig. 14. Temperature effect on the critical state line (CSL).

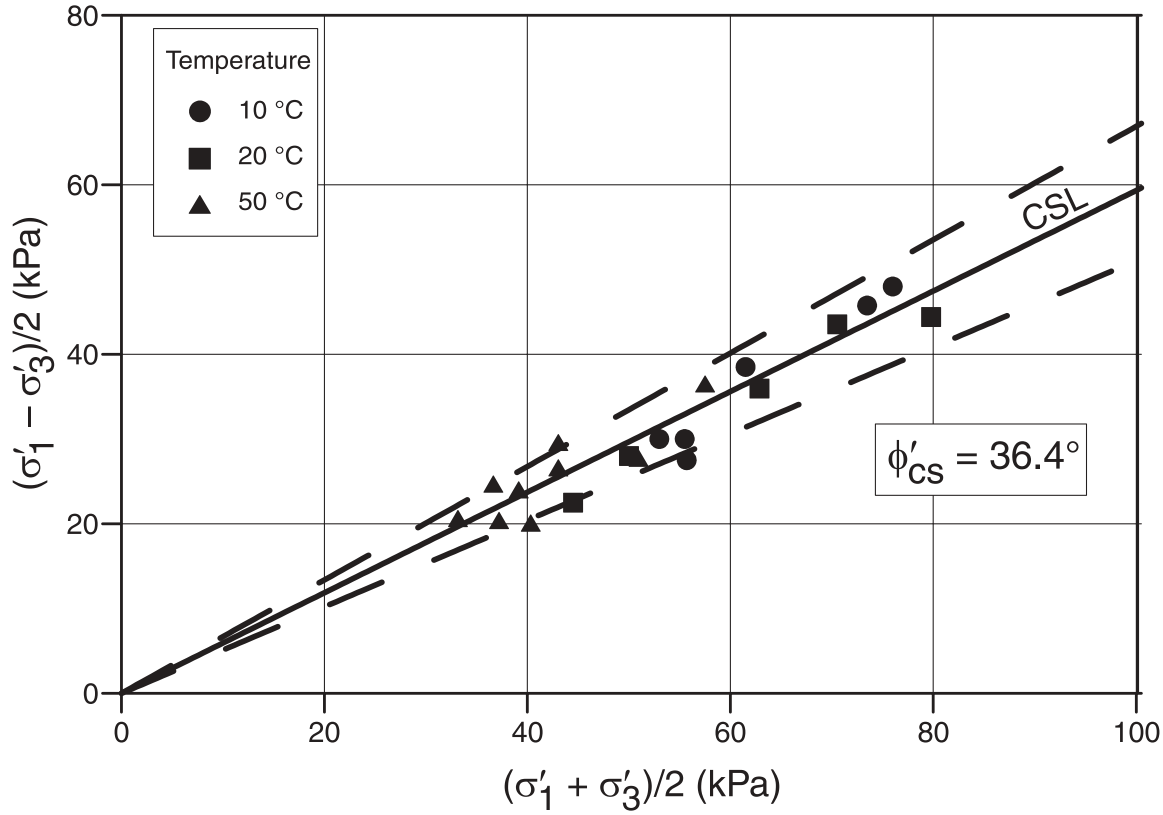


Fig. 15. Temperature effect on the critical state line in a $\Delta V/V_0$ – p' plane.

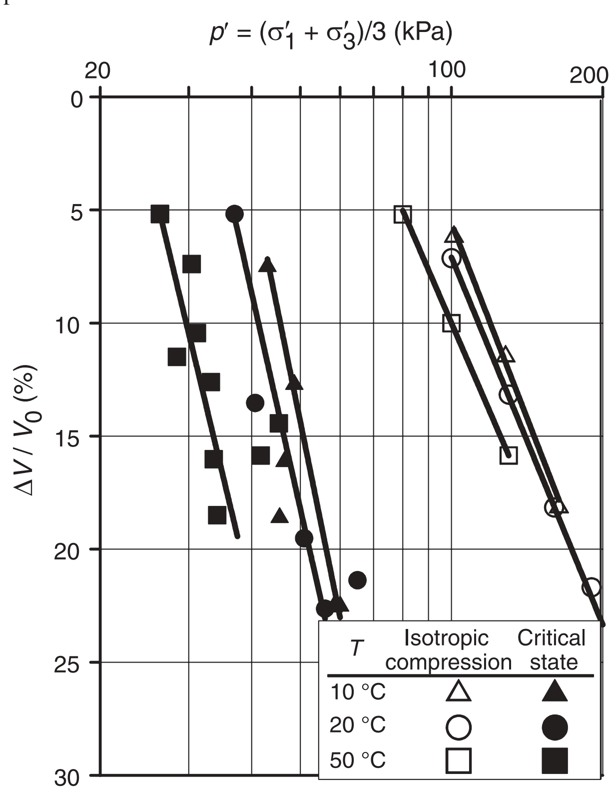
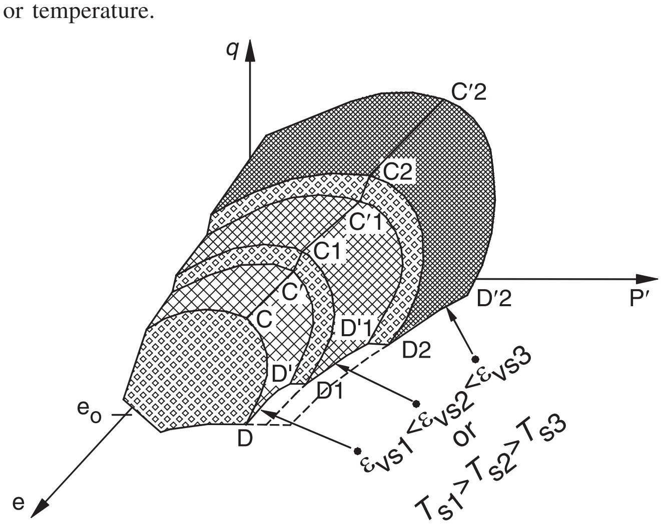


Fig. 16. Schematic variation of limit state surface with strain rate or temperature.



which states that the ratio of vertical yield stresses obtained at two different strain rates or temperatures is the same at any strain or void ratio. This behaviour was observed under one-dimensional conditions for CRS tests (Figs. 3, 4).

There are viscous models that consider the influence of strain rate on limit state (Yin et al. 1994; Rowe and Hinchberger 1998; Kim and Leroueil 2001) and models that consider the influence of temperature on limit state (Hueckel and Borsetto 1990; Laloui and Modaressi 1997; Graham et al. 2001). To the authors' knowledge, however, there is no model that accounts for both strain rate and temperature effects. It is thought that the tests results obtained on St-Roch-de-l'Achigan clay show the importance of viscosity (and anisotropy) on the behaviour of natural soft clays and could be used as an experimental basis to verify a numerical viscous model for natural clays.

6.2. Temperature, strain rate, and microstructuring

Evidence of the influence of microstructure on soil behaviour has been found in a wide range of geomaterials, as shown by Leroueil and Vaughan (1990). The main effect of microstructure is to increase the stiffness and the size of the limit state curve of the soil, and thus increase its strength and preconsolidation pressure to a level that cannot be normally reached by the soil at the same void ratio. If clay microstructure is destroyed by straining in compression, shear, or swelling (Leroueil and Vaughan 1990), its effects disappear. Experience has shown, however, that some microstructure can be partly recovered with time (aging process).

With sensitivity between 30 and 50, St-Roch-de-l'Achigan clay is obviously microstructured, and this microstructure is destroyed with the development of plastic strains, particularly when the vertical yield stress is exceeded during one-dimensional compression tests. There is evidence, however, of microstructuring of St-Roch-de-l'Achigan clay during CRS tests carried out at high temperatures and low strain rates. The CRS tests performed at a temperature of 50 °C and strain rates from 10^{-5} to 10^{-7} s^{-1} are shown in Fig. 17. In the overconsolidated range and just after the passage of the vertical yield stress, the behaviour is as generally observed, with a vertical yield stress increasing with an increase in strain rate. In the normally consolidated range, however, the compression curves converge, which is at variance with the stress – strain – strain rate – temperature (σ_v', ε_v, $\dot{\varepsilon}_v$, T) model proposed by Leroueil et al. (1985) and Boudali et al. (1994) and what was observed in Fig. 3. This is attributed to microstructuring of St-Roch-de-l'Achigan clay at 50 °C as the strain rate decreases.

Boudali et al. (1994) suggested that one-dimensional compression of clays could be described by a unique normalized vertical effective stress – strain relationship ($\sigma_v'/\sigma_p'(\dot{\varepsilon}_1, T)$ – ε_1), where $\sigma_p'(\dot{\varepsilon}_1, T)$ is the vertical yield stress at the considered strain rate $\dot{\varepsilon}_1$ and temperature T. All the compression curves obtained from CRS tests performed on St-Roch-de-l'Achigan clay are shown in Fig. 18, normalized with respect to $\sigma_p'(\dot{\varepsilon}_1, T)$. Seven tests are inside a very narrow range and confirm the validity of the model proposed by Boudali et al. However, at 30 °C and a strain rate of 6.75×10^{-7} s^{-1} and at 50 °C and strain rates of 3.38×10^{-6} s^{-1} and lower (see structured (st) specimens in Fig. 18), the compression curves are above the previously mentioned reference curve. Also, the lower the strain rate and the higher the temperature, the farther the normalized compression curve is from the reference curve. As shown in Fig. 18, the curve farthest from the reference curve is that performed at 50 °C at a strain rate of 10^{-7} s^{-1}. These results indicate that microstructure develops in St-Roch-de-l'Achigan clay and that the process increases with an increase in temperature.

A special test program including CRS tests and special oedometer tests (IL tests) has been established to verify this behaviour. In the IL test, the soil was first loaded by steps at a temperature of 10 °C up to a vertical effective stress of 140 kPa, in excess of the vertical yield stress of the clay (Fig. 19*a*). The specimen was then heated to 20, 35, and 50 °C in steps with duration of at least 48 h. The specimen

Fig. 17. Evidence of microstructuring in one-dimensional compression due to low strain rate.

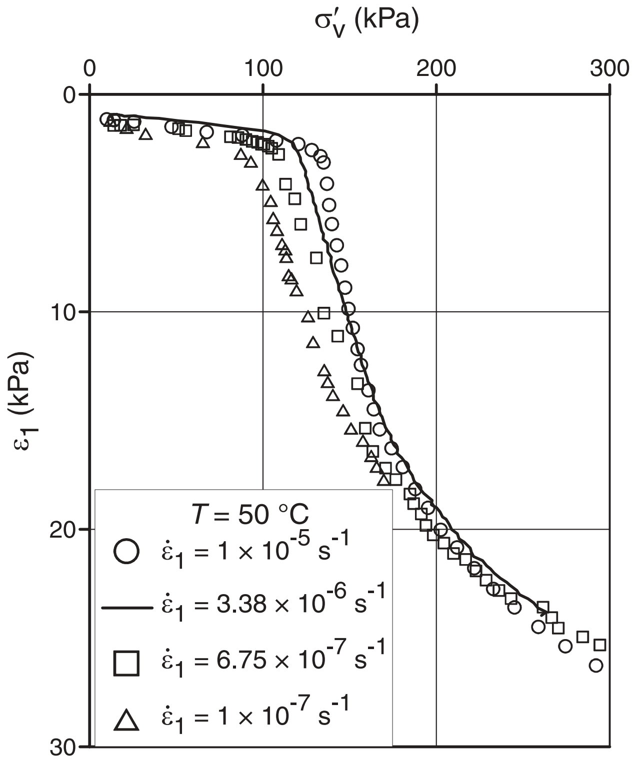


Fig. 18. Normalized compression curves from the CRS and IL tests. st, specimen that was structured during the test.

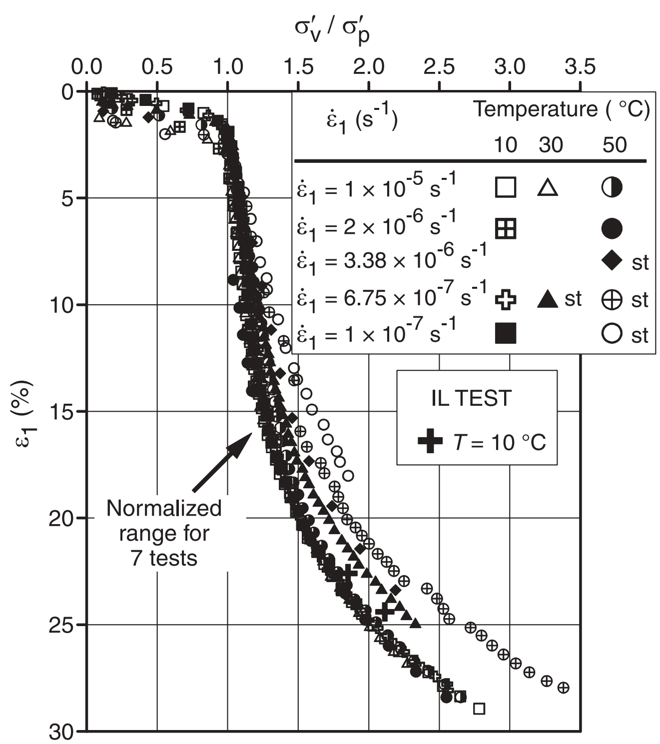
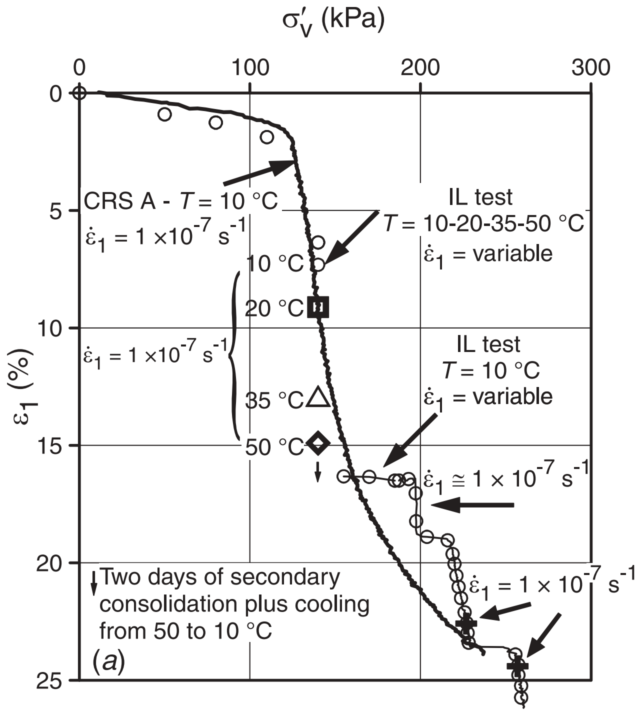


Fig. 19. Evidence of microstructuring in one-dimensional compression due to high temperature: (*a*) CRS test at 10 °C and 10^{-7} s^{-1} and IL test at different temperatures; (*b*) CRS tests at 10 or 50 °C and 10^{-7} s^{-1}.



was then cooled from 50 to 10 °C and then loaded in three steps up to a vertical stress of 260 kPa. Figure 19*a* shows the compression curves obtained from the IL test, with points at a strain rate of 10^{-7} s^{-1} plotted together with the continuous compression curve obtained from the CRS test (CRS A) carried out at 10 °C and 10^{-7} s^{-1}. During the first stages of loading at 10 °C, the IL test and the CRS test coincide well. With heating, as expected, soil compresses and moves below the CRS curve at 10 °C. After cooling from 50 to 10 °C at an axial strain of about 16.5%, however, it appears that the compression curve obtained upon reloading moves well above the CRS compression curve, with a vertical yield stress about 32% larger than the vertical effective stress on the CRS compression curve, at the same vertical strain. As vertical strain develops, soil microstructure is broken down and both IL and CRS curves merge to become coincident.

To confirm the effect of temperature, the CRS test performed at 50 °C and 10^{-7} s^{-1} (shown in Fig. 17) was stopped at ε_1 = 17.5% and the specimen was cooled to 10 °C. Some swelling and relaxation occurred during the cooling from 50 to 10 °C. Then the CRS was resumed at the same strain rate of 10^{-7} s^{-1} (CRS B). The compression curve of this test is shown in Fig. 19*b*, with the continuous compression curve of CRS A performed at 10 °C and a strain rate of 10^{-7} s^{-1}. The compression curves obtained from the CRS tests performed at 10^{-7} s^{-1} and temperatures of 10 °C for CRS A and 50 °C for CRS B converge to merge at a vertical strain of about 17.5%, indicating development of microstructure. Microstructuration of specimen B is confirmed by its compression curve after cooling at 10 °C. It indeed shows a vertical yield stress of 209 kPa, about 23% larger than the vertical effective stress on curve A at the same vertical strain. Interestingly, destructuration at yielding corresponds to a collapse of the soil with a slight decrease in vertical effective stress. The compression curve then progressively moves toward compression curve A obtained at the same strain rate and temperature. This confirms that the soil compressed at 50 °C and developed some microstructure at a strain rate of 10^{-7} s^{-1}.

These phenomena were observed in one-dimensional compression tests. They could also exist in the triaxial tests, at least for tests performed at a temperature of 50 °C. This could possibly explain why the peak strengths obtained in the overconsolidated range were essentially about the same at 20 °C and at 50 °C. On the other hand, there is no evidence that the isotropic and anisotropic triaxial compression tests were influenced by microstructuring.

The possibility for some clays to develop some microstructure at low strain rates has already been evidenced by Leonards and Altschaeffl (1964) and Leroueil et al. (1996). The results of the present study show that the importance of microstructuring, or at least its rate of development, increases with an increase in temperature. This may be a limitation to the stress – strain – strain rate – temperature (σ_v', ε_v, $\dot{\varepsilon}_v$, T) model proposed by Leroueil et al. (1985) and Boudali et al. (1994). On the other hand, these phenomena may have important practical implications.

7. Conclusions

An experimental study has been carried out on the influence of strain rate and temperature on the mechanical behaviour of a sensitive clay from Quebec. The main conclusions are summarized as follows:

(1) The vertical yield stress defined in one-dimensional compression tests increases with an increase in strain rate and decreases when temperature increases according to eqs. [2] and [3]. The hydraulic conductivity of soil also depends on temperature.
(2) The oedometer test results performed at relatively low temperatures and high strain rates confirm that, as proposed by Boudali et al. (1994), clay behaviour is controlled by a vertical effective stress – strain – strain rate – temperature model and that, once normalized with respect to the vertical yield stress associated with the strain rate and temperature of the test, all the compression curves coincide.
(3) Triaxial isotropic and anisotropic compression tests show that it is not only the vertical yield stress that is strain rate and temperature dependent, but also the entire limit state curve.
(4) As a consequence, the peak strength envelope of the overconsolidated soil is lowered when temperature increases.
(5) Undrained compression tests performed in the normally consolidated range show that the friction angles at the peak and at large deformation (critical state) are essentially independent of temperature. On the other hand, generated pore pressure increases when strain rate decreases.
(6) It is thought that this set of data could be used for the development or the verification of thermo-viscoplastic models for clays.
(7) It appears, however, that at high temperatures and low strain rates, microstructuring of the clay develops in the normally consolidated range, indicating limitations to the stress – strain – strain rate – temperature model proposed by Boudali et al. (1994). For the time being, it is impossible to say if this behaviour observed in the laboratory for St-Roch-de-l'Achigan clay could also exist for other clays and in in situ conditions.

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