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VISCOUS BEHAVIOUR OF NATURAL CLAYS

TENUE VISQUEUSE DES ARGILES NATURELLES

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SYNOPSIS: Experimental studies show that the behaviour of natural clays during one-dimensional compression is strongly influenced by strain rate and temperature. The preconsolidation pressure is a function of both temperature and strain rate, and a general equation is proposed. Also, when effective stresses observed in oedometer tests performed at various strain rates and temperatures are normalized with respect to the preconsolidation pressure corresponding to the testing strain rate and temperature, all the data come on a unique normalized stress-strain curve. This normalized curve depends on the mineralogy and geological history of the clay. The general one-dimensional compression behaviour of natural clays can thus be simply described by two functions.

INTRODUCTION

The effects of temperature on the engineering properties of soils have been thoroughly studied in the sixties and a specialty conference on "The effects of temperature and heat on engineering behavior of soils" was held at Washington in 1969. More recently, a renewal of interest for this topic has come, mainly in relation with new concerns such as nuclear waste isolation and the use of soil deposits for heat energy storage. Experimental studies on natural soft clays (Eriksson, 1989; Tidfors and Sällfors, 1989) as well as the development of constitutive equations (Hueckel and co-workers, in particular Hueckel and Borsetto, 1990, and Hueckel and Baldi, 1990) have been performed. All these studies confirm the viscous nature of clays.

Studying the rheology of natural clays, Leroueil et al. (1985) showed that, during one-dimensional compression, the behaviour is entirely controlled by a unique effective stress-strain-strain rate (σ'_v - ε_v - $\dot{\varepsilon}_v$) relationship. They also showed that this relationship can be simply described by two curves, one giving the variation of the preconsolidation pressure with strain rate ($\sigma'_p = f(\dot{\varepsilon}_v)$) and the other presenting the normalized stress-strain ($\sigma'_v/\sigma'_p(\dot{\varepsilon}_v) = g(\varepsilon_v)$) curve.

As viscosity means effect of temperature as well as effect of strain rate, it appeared interesting to examine how the model found by Leroueil et al. (1985) could be extended to include the influence of temperature on clay behaviour. For this purpose, Constant Rate of Strain (CRS) oedometer tests were performed on three Eastern Canada clays, at various strain rates and temperatures. Herein, the test results are described and a generalized rheological model for one-dimensional compression is proposed.

TEST EQUIPMENT AND PROCEDURE

The oedometer tests were performed on specimens 20 mm high and 71 mm in diameter. The specimens were trimmed in the humid room at 8°C, where they were previously stored. They were then mounted in the oedometer cell, in the main laboratory, at a temperature of 20°C, and subjected to a vertical effective stress of 10 kPa, with an applied back pressure of 100 kPa. The vertical effective stress of 10 kPa was applied to insure a good control of the vertical strain during the CRS tests, but also during the changes in temperature. All the specimens were maintained in these conditions during 24 hours.

Three different temperatures were used in this programme, 5, 20 and 35°C. For the tests at 20°C, the oedometer cell was simply put on a triaxial press and the specimen was compressed at a constant rate of displacement. For the tests at 5°C, the oedometer cell was put on a press in a controlled temperature room during 24 hours before starting the compression test; the time necessary to have in the specimen the same temperature as in the room was about 7 hours. For the tests at 35°C, the oedometer cell was submerged in a water bath, and maintained at a constant temperature with a thermostat and a small pump continuously circulating the water. The cell was maintained in these conditions during 24 hours before starting the compression test.

In all these CRS tests, the mean effective vertical stress was calculated using the equation:

$$\sigma'_v = \sigma_v - u_o - 0.67\ (u_b - u_o) \quad (1)$$

where σ_v is the total applied stress, u_o is the applied back pressure and u_b is the pore pressure measured at the base of the specimen.

TESTED CLAYS

The clays tested in this study were sampled with the 200 mm diameter Laval sampler (La Rochelle et al., 1981) on the sites of Berthierville, Louiseville and Saint-Jean-Vianney in the Province of Québec. The main geotechnical properties of these materials are given in Table 1. It can be seen in particular that their preconsolidation pressures vary considerably from 58 kPa at Berthierville to about 1060 kPa at Saint-Jean-Vianney.

Because of data available on this clay (Leroueil et al., 1988), the main research programme was performed on Berthierville clay. Three temperatures (5, 20 and 35°C) and three strain rates (10^{-5} s^{-1}, 1.5 x 10^{-6} s^{-1} and 1.6 x 10^{-7} s^{-1}) were considered. On the two other clays, two series of tests were performed at the same temperatures, but only at the strain rate of 1.5 x 10^{-6} s^{-1}.

TEST RESULTS

Strains due to changes in temperature

The vertical strains were measured when the temperature was changed from 20°C to 5 or 35°C. As already observed by other researchers, a change in temperature resulted in a change in void ratio. For the three

Site	Depth (m)	w (%)	I_p (%)	C_u (kPa)	σ'_p* (kPa)
Berthierville	3.15-3.50	62	25	12	58
Louiseville	8.70-8.76	72	39	43	175
"	8.76-8.82	68	39	43	198
St-Jean-Vianney	4.44-4.54	42	14	192	980
"	5.60-5.72	42	14	192	1060

* σ'_p at 20 °C and $1.5 \times 10^{-6} s^{-1}$

Table 1. Geotechnical properties of tested clays

clays tested, a reduction of the temperature from 20°C to 5°C resulted in a swelling of 0.2 to 0.3%, and an increase from 20°C to 35°C gave a compression strain of about the same amount.

Berthierville clay

Tests results obtained on the Berthierville clay are shown on figure 1. Figures 1-a and 1-b present respectively the vertical strain and the pore pressure versus the vertical effective stress for the tests performed at a strain rate of $1.0 \times 10^{-5} s^{-1}$. Figures 1-c and 1-d, and figures 1-e and 1-f, present the same results for the tests performed at strain rates of $1.5 \times 10^{-6} s^{-1}$ and $1.6 \times 10^{-7} s^{-1}$ respectively.

Except for the test performed at 20°C, at a strain rate of $1.0 \times 10^{-5} s^{-1}$ which is superimposed to the tests performed at the same strain rate, but at a temperature of 35°C (Fig. 1-a), it can be seen that, at a given strain rate, the smaller the temperature, the higher is the effective stress at a given strain. Also, at a given temperature, the higher the strain rate, the higher is the effective stress at a given strain. For example, at 5°C, the preconsolidation pressure increases from 62 to 80 kPa when the strain rate increases from $1.6 \times 10^{-7} s^{-1}$ to $1.0 \times 10^{-5} s^{-1}$. This is consistent with rate effects previously observed by Crawford (1964), Sällfors (1975) and Leroueil et al. (1983).

It can also be seen on Figs. 1-a, 1-c and 1-e that, in the overconsolidated range, the smaller the temperature, the higher is the strain modulus. Also, the strain at the passage of the preconsolidation pressure is not significantly influenced by the strain rate or the temperature.

The pore pressure measured at the base of the specimen is also of interest (Figs 1-b, 1-d and 1-f). It is very small when the soil is in the overconsolidated range, and then increases to values which depend on the strain rate, from about 30 kPa at $\dot{\varepsilon}_v = 1.0 \times 10^{-5} s^{-1}$ to about 1 kPa at $\dot{\varepsilon}_v = 1.6 \times 10^{-7} s^{-1}$. At a given strain rate, it also varies with the temperature in a manner which is worth mentioning. If the tests carried out at a strain rate of $1.0 \times 10^{-5} s^{-1}$, at temperatures of 5°C and 35°C, are considered (Fig. 1-b), because the preconsolidation pressure at 5°C is higher, the pore pressure at this temperature starts increasing at a larger effective stress; however, because the hydraulic conductivity is smaller at this temperature, the measured pore pressure becomes higher. At an effective stress of 200 kPa, this pore pressure is equal to 32 kPa at 5°C and 18 kPa at 35°C.

According to Smith and Wahls (1969) who assumed a parabolic shape of the pore pressure isochrone, the hydraulic conductivity k, and its variation with compression, can be deduced from CRS tests, using the equation:

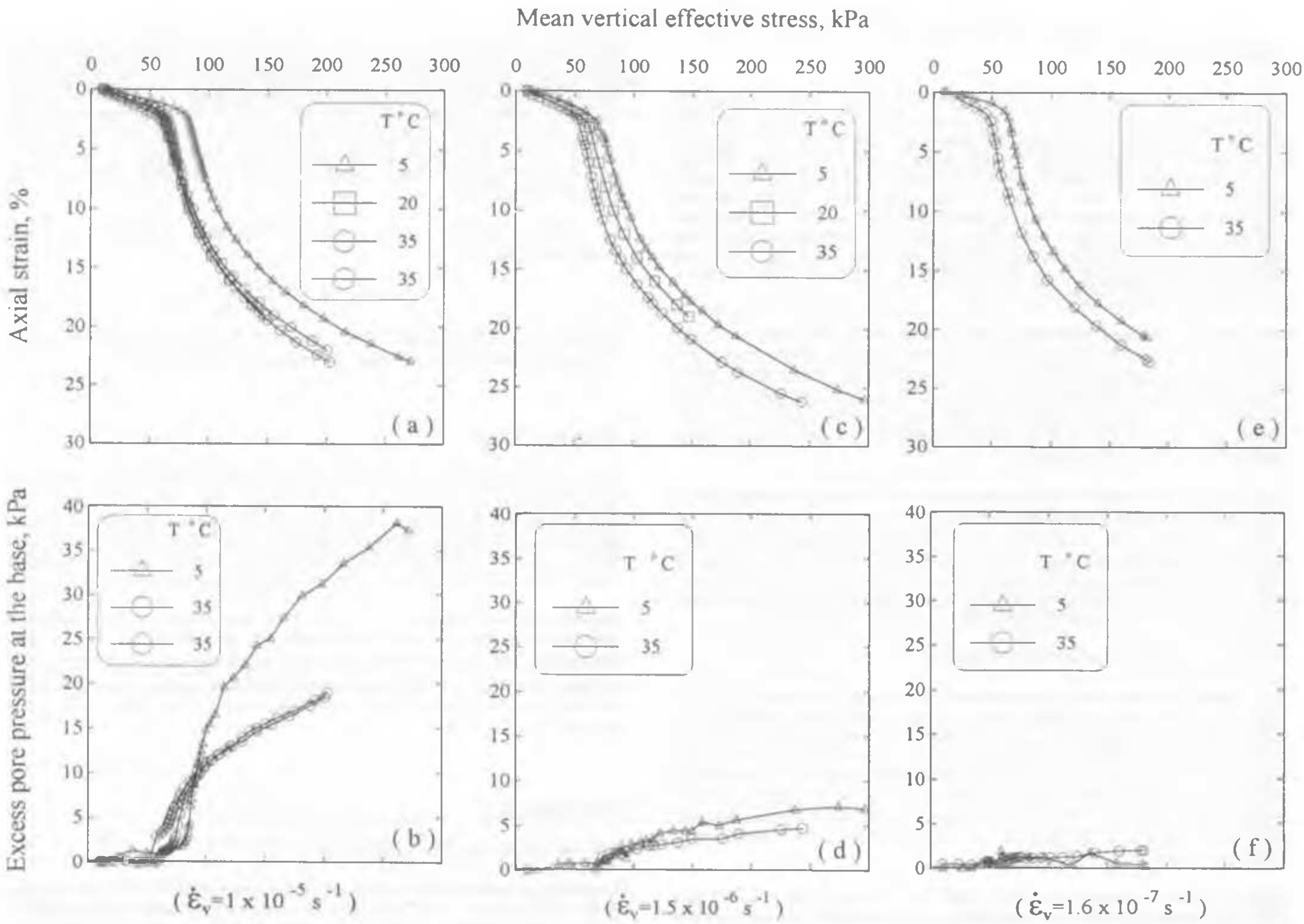

Fig. 1. Effects of strain rate and temperature on the one-dimensional consolidation behaviour of Berthierville clay

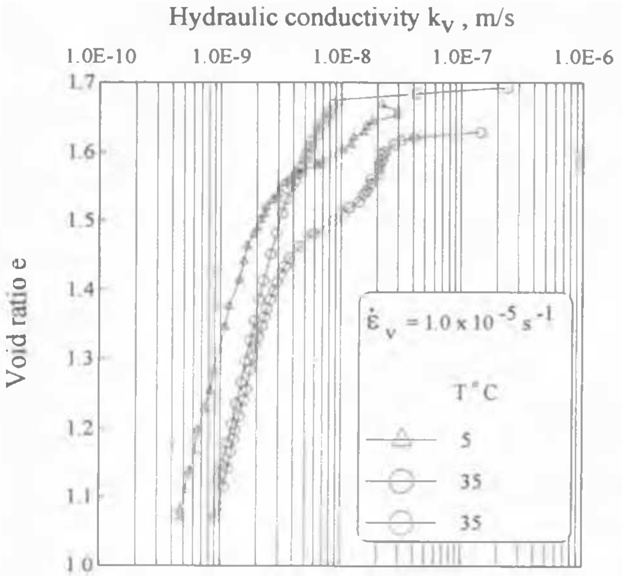

Fig. 2. Hydraulic conductivities deduced from CRS tests performed on Berthierville clay, at temperatures of 5 and 35°C

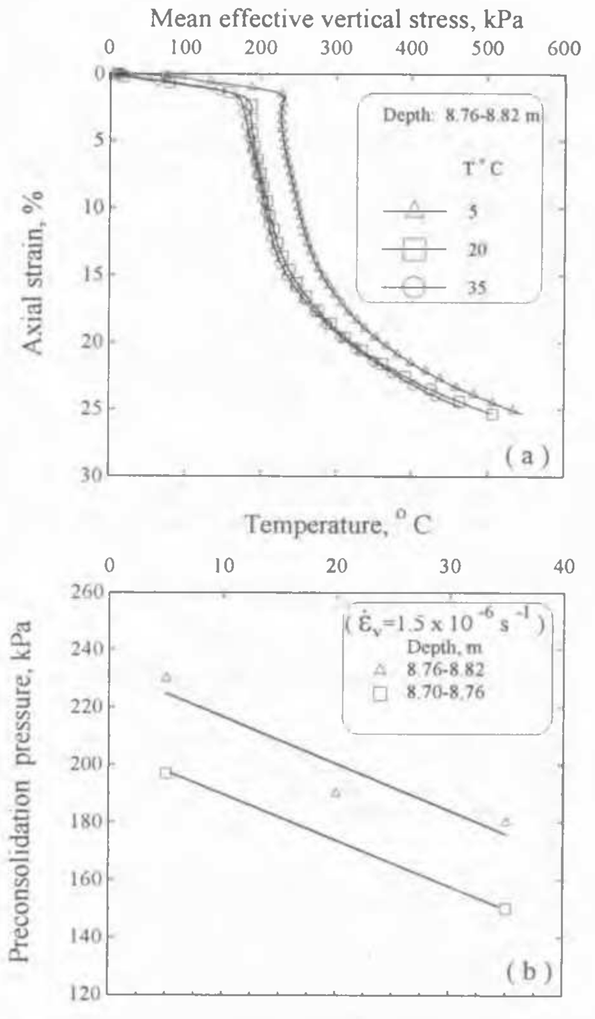

Fig. 3. Constant rate of strain (CRS) oedometer tests performed at various temperatures on Louiseville clay ($\dot{\varepsilon}_v$ = 1.5 x 10^{-6} s^{-1})

$$k = H^2 \gamma_w \dot{\varepsilon}_v / 2(u_b - u_o) \quad (2)$$

in which H is the height of the specimen, γ_w is the unit weight of water, u_b is the pore pressure at the base of the specimen and u_o is the back pressure. The void ratio-hydraulic conductivity relationships deduced from the tests performed at a strain rate of 1.0 x 10^{-5} s^{-1} are shown on Fig. 2. They are irregular at high void ratios, which can be explained by the fact that the pore pressure isochrone is not parabolic when the soil is close to the preconsolidation pressure (Tavenas et al., 1983). At void ratios smaller than 1.4 however, the logarithm of hydraulic conductivities decreases linearly with the void ratio, that obtained at 5°C being smaller than those obtained at 35°C by a factor of about 2. This is essentially due to the change in the viscosity of the water which increases by a factor of 2.1 when the temperature decreases from 35°C to 5°C. Habibagahi (1977) came to similar conclusions.

Other Canadian clays

Figure 3-a shows the test results obtained on Louiseville clay, on samples taken at a depth of 8.76 - 8.82 m. Even if the curves obtained at 20 and 35°C are very close, the effect of temperature is clearly evidenced. Figure 3-b presents, as a function of the temperature, the preconsolidation pressure deduced from these tests; it also presents results of another series of tests performed on specimens taken at a depth of 8.70 -8.76 m. Even if this depth is very close to that of the other series, the results were significantly different both in terms of preconsolidation pressure and stress-strain behaviour; they have thus been considered separately.

Even if not as well defined as for the other clays, a temperature effect can also be seen on Fig. 4 where the test results obtained on the stiff and sensitive Saint-Jean-Vianney clay are shown.

Natural Swedish clays

In relation with projects of heat energy storage in clay deposits, Eriksson (1989) and Tidfors and Sällfors (1989) studied the influence of temperature on the compression characteristics of several natural clays from Sweden. For the six materials studied, these authors found a temperature effect very similar to that described here. Figure 5 presents the results obtained on Luleå clay.

DISCUSSION

For the reconstituted and normally consolidated clays tested in the sixties, it appeared that the change in void ratio associated to a change in temperature was about the same at all stresses. It was thus concluded that the compressibility of these materials was essentially unaffected by temperature (Campanella and Mitchell, 1968). Experience with natural clays (Tidfors and Sällfors (1989) and this study) shows that under a small effective stress, i. e. in the overconsolidated range, the change in void ratio due to a change in temperature is relatively small. As there is an important temperature effect on the normally consolidated branch of the compression curve and on the preconsolidation pressure, it follows that the compressibility of natural clays can be said temperature dependent.

Studying the effects of strain rate, Leroueil et al. (1985) showed that one-dimensional clay behaviour could be described by one curve giving the variation of the preconsolidation pressure with strain rate and another curve representing the normalized effective stress-strain behaviour. As previously seen, the preconsolidation pressure is dependent not only on the strain rate, but also on the temperature (Figs. 1-a, 1-c, 1-e, 3, 4 and 5). It can thus be expressed as a function of both parameters:

$$\sigma'_p = f(T, \dot{\varepsilon}_v) \quad (3)$$

Figure 6 shows this relationship for the Berthierville clay in a σ'_p - T diagram (fig. 6-a) and in a log $\dot{\varepsilon}_v$ - log σ'_p (Fig. 6-b, including the data previously obtained by Kabbaj, 1985). Figure 7 shows all the stress-strain curves presented in Fig. 1, normalized with respect to the preconsolidation pressure corresponding to the same strain rate and temperature (Fig. 6). They all come along the same line, which can be described by the equation:

$$\sigma'_v / \sigma'_p(T, \dot{\varepsilon}_v) = g(\varepsilon_v) \quad (4)$$

Equations (3) and (4) represent the generalized form, including

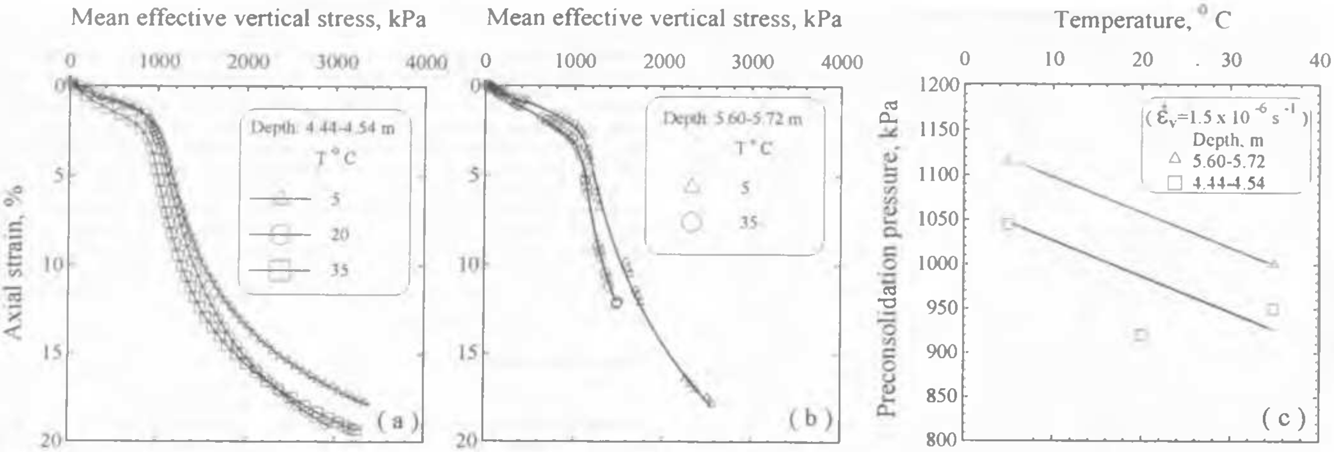

Fig. 4. Constant rate of strain (CRS) oedometer tests performed at various temperatures on St-Jean-Vianney clay ($\dot{\varepsilon}_v$ = 1.5 x 10^{-6} s^{-1})

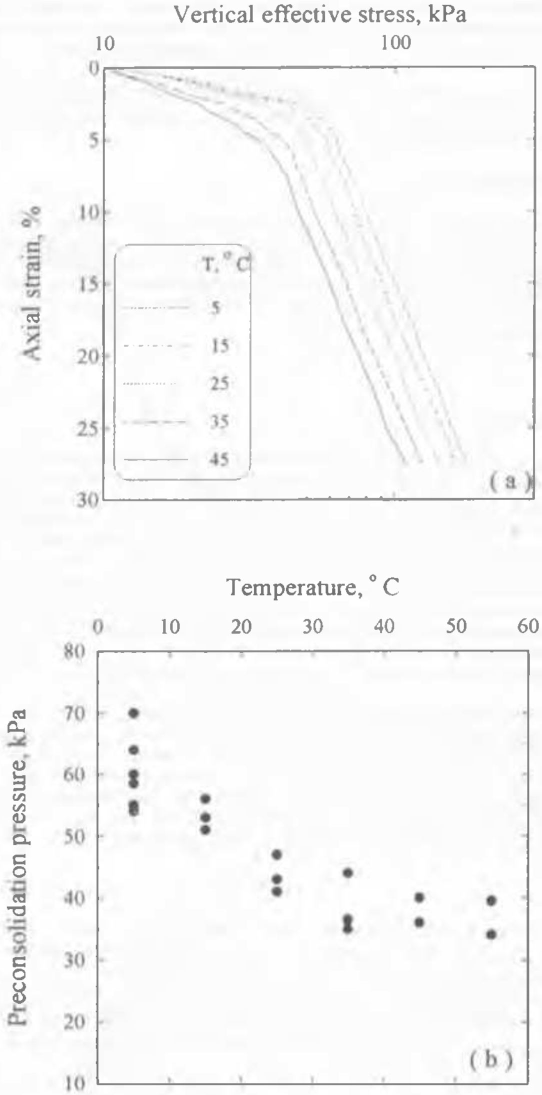

Fig. 5. Oedometer tests performed on Luleå clay at various temperatures (From Eriksson, 1989)

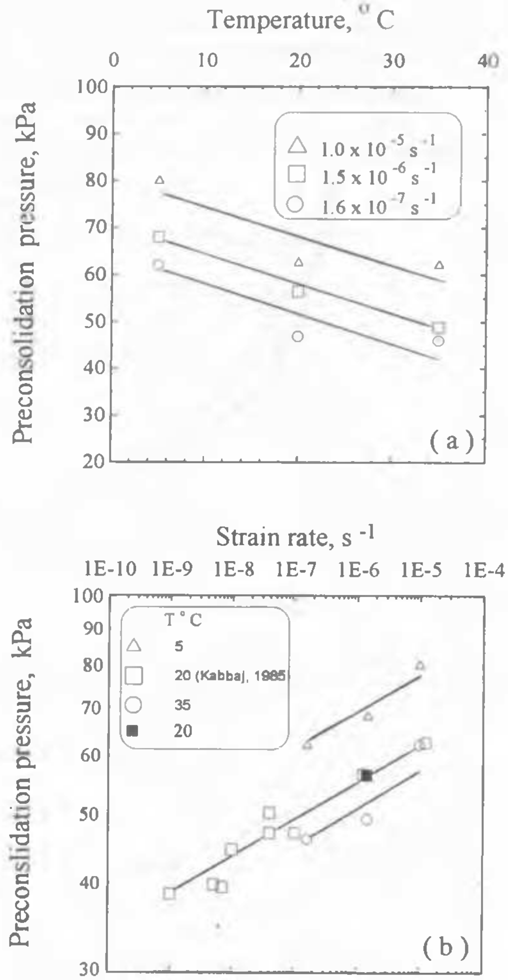

Fig. 6. Variation of the preconsolidation pressure of Berthierville clay with strain rate and temperature. (a) in a T - σ'_p diagram; (b) in a log $\dot{\varepsilon}_v$ - log σ'_p diagram

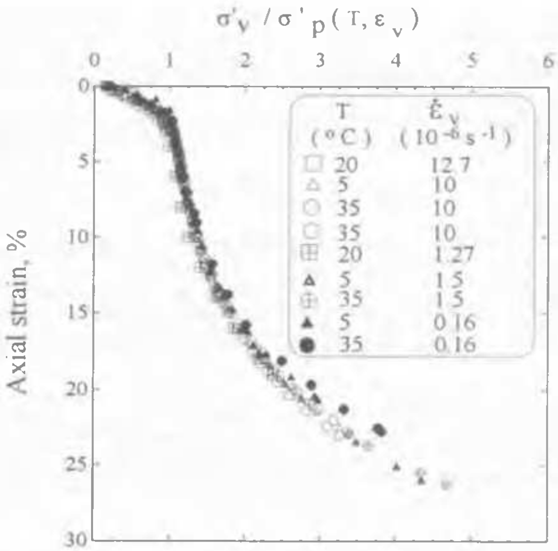

Fig. 7. Normalized effective stress - strain curve for Berthierville clay

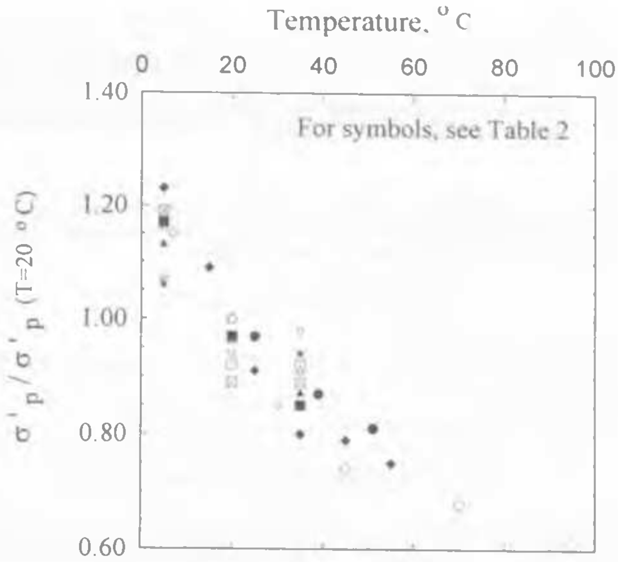

Fig. 8. Variation of the normalized preconsolidation pressure ($\sigma'_p/\sigma'_p(20°C)$) with temperature

Site	Depth (m)	I_p (%)	Type of oedometer test	σ'_p (20°C) (kPa)	Range of temperature, °C	Reference	Symbol used in Fig. 8
Berthierville	3.15-3.50	25	CRS, $\dot{\varepsilon}_v=1.0 \times 10^{-5} s^{-1}$	68.5	5-35	Present study	□
"	"	"	CRS, $\dot{\varepsilon}_v=1.5 \times 10^{-6} s^{-1}$	58	"	"	■
"	"	"	CRS, $\dot{\varepsilon}_v=1.6 \times 10^{-7} s^{-1}$	52.5	"	"	▣
Louiseville	8.70-8.76	39	CRS, $\dot{\varepsilon}_v=1.5 \times 10^{-6} s^{-1}$	175	"	"	▴
"	8.76-8.82	39	"	198	"	"	▲
St-Jean-Vianney	4.44-4.54	14	"	980	"	"	★
"	5.60-5.72	14	"	1060	"	"	▿
Argile noire	--	32	Conventional	--	20-95	Despax, 1975	○
Illite	--	--	Isotropic consolidation	--	25-51	Campanella and Mitchell, 1968	●
Bäckebol	3.0-7.0	60	CRS, 0.0024mm/min	54	7-30	Tidfors and Sällfors, 1989	◇
Luleå	4.0	60	Conventional	50	5-55	Eriksson, 1989	◆

Table 2. Clays considered in Fig. 8

temperature effects, of the rheological model proposed by Leroueil et al. (1985).

The fact that the effective stress-strain curves obtained at various temperatures and strain rates can be normalized means that they are parallel in a ε_v or e - log σ'_v diagram, which is consistent with observations previously made by Campanella and Mitchell (1968), Despax (1975), Eriksson (1989), etc.

The shape of the normalized stress-strain curve (Eq. 4) is a function of the fabric and the structure of the clay, and thus its mineralogy and geological history. It thus varies from clay to clay. The $\sigma'_p = f(T, \dot{\varepsilon}_v)$ relationship, representing the viscous characteristics of the clay skeleton, can be examined in more details. Leroueil et al. (1983, 1985) showed that, when the preconsolidation pressure is normalized with respect to the preconsolidation pressure obtained at a reference strain rate $\dot{\varepsilon}_{vo}$, the normalized $\sigma'_p/\sigma'_p(\dot{\varepsilon}_{vo})$ - $\dot{\varepsilon}_v$ relationships become unique for a large variety of Champlain sea clays. In a log $\sigma'_p/\sigma'_p(\dot{\varepsilon}_{vo})$ - log $\dot{\varepsilon}_v$ diagram, these relationships are essentially linear and can be expressed by the following equation:

$$\log\left[\sigma'_p(\dot{\varepsilon}_v,T_o)/\sigma'_p(\dot{\varepsilon}_{vo},T_o)\right] = A \log\left[\dot{\varepsilon}_v/\dot{\varepsilon}_{vo}\right] \quad (5)$$

or:

$$\sigma'_p(\dot{\varepsilon}_v,T_o) = \sigma'_p(\dot{\varepsilon}_{vo},T_o)\left[\dot{\varepsilon}_v/\dot{\varepsilon}_{vo}\right]^A \quad (6)$$

From the data presented by Leroueil et al. (1983, 1985), A would be approximately equal to 0.05. Mesri and Choi (1984) indicated that this parameter A is close to the ratio $C_{\alpha e}/C_c$, with $C_{\alpha e}$, secondary compression index, and C_c, compression index. From data obtained on a large variety of materials, Mesri and Castro (1987) concluded that the $C_{\alpha e}/C_c$ ratio is equal to about 0.04 for inorganic clays and slightly higher, about 0.05 for highly organic plastic clays. Even if the data base is limited to the results obtained on the Berthierville clay (Fig. 6-b), the shape of this relationship does not seem to be affected by the temperature. Equations (5) and (6) thus seem to be general, with A equal to 0.04 - 0.05.

Figure 8 shows the normalized preconsolidation pressure (σ'_p / σ'_p(20°C and same strain rate)) as a function of the temperature for a variety of intact and reconstituted clays. There is a clear tendency for the ratio to decrease when the temperature increases but there is some scattering and the relationship varies from clay to clay. In particular, as already noticed by Tidfors and Sällfors (1989), the effect of temperature seems to increase with the plasticity of the clay. However, the number of materials studied is to small to definitely conclude.

If it is assumed that, at least for a given range of temperature, the preconsolidation pressure varies linearly with the temperature, the $\sigma'_p / \sigma'_p(T_0)$ - T relationship can be written as follows:

$$\sigma'_p(\dot{\varepsilon}_{v0}, T) = \sigma'_p(\dot{\varepsilon}_{v0}, T_0)[1 + CT_o - CT] \quad (7)$$

From Fig. 8, an average C value for temperatures between 5 and 40°C would be about 0.009°C^{-1}.

Combining equations (6) and (7), it comes:

$$\sigma'_p(\dot{\varepsilon}_v, T) = \sigma'_p(\dot{\varepsilon}_{v0}, T_0)\,[\dot{\varepsilon}_v/\dot{\varepsilon}_{v0}]^A[1 + CT_o - CT] \quad (8)$$

Knowing parameters A and C, the use of equations (4) and (8) allows the determination of the one-dimensional behaviour of a clay for any temperature or strain rate history.

CONCLUSION

Experimental studies show that the behaviour of natural clays during one-dimensional compression is strongly influenced by strain rate and temperature. This behaviour can be described by two functions. The first one gives the variation of the preconsolidation pressure with strain rate and temperature; an equation (8) is proposed for this function. The second one gives the normalized effective stress-strain curve; it varies from clay to clay, depending on its mineralogy and geological history. The proposed model is thus a generalization of the model previously suggested by Leroueil et al. (1985).

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