Temperature effects on the mechanical properties of slates in triaxial compression test

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Abstract: High geothermal temperatures appear to be unfavorable for the construction of tunnels in slate rocks with high overburden. To investigate the mechanical characteristics of slates at various levels of geothermal temperature, conventional triaxial compression tests at different levels of confining stress were carried out at 4 different temperatures from 20°C to 120°C. The obtained results show high confining pressures weaken the thermal effects on rock mechanical characteristics while higher temperatures enhance the effect of confining pressure. At higher levels of confining stress the thermal effects on the rock strength characteristics decrease. The higher the temperature, the larger is the effect of confining pressure on the mechanical characteristics of the slate. Increase of temperature leads to a decrease of the peak strength but increases the deformability and ductility of the slate, the thermo effect on the peak strength and Poisson's ratio is larger than on the elastic modulus. Higher temperatures reduce the shear strength of slate, the decrease is mainly caused by a decrease of the cohesion. In general, the slate samples fail in shear failure.

Keywords: Temperature effect; Slate; Mechanical feature; Triaxial test

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Introduction

In many major infrastructural projects in South West China deep seated tunnels have to be constructed in rock strata, such as slates. These deep underground environments show high levels of geo-stress levels and geothermal temperatures. The mechanical properties of slate under high confining pressure and geothermal conditions must be understood for a correct design of the stability of the excavations for deep seated tunnels in slates.

The effect of heating and cooling on the mechanical properties of granite, sandstone, coarse sandstone and marble have been investigated (e.g., Alm 1985; Zhu et al. 2007; Su et al. 2008; Yin et al. 2009; Li et al. 2011). Xu and Liu (2000), Zhang et al. (2009), conducted uniaxial compression tests under constant high temperatures up to 800°C on granite, marble, limestone, and sandstone, while Lau et al. (1995) and Wan et al. (2008) investigated the mechanical properties of granite under high temperatures up to 600°C with triaxial compression tests. Most of these studies have focused on the thermo-mechanical characterization of engineered and geological barriers for geological disposal of

Table 1 Mechanical performance of some rock types

Mechanical properties	Rock types	Temperature			
		20°C	75°C	100°C	150°C
Peak strength σ_c (MPa)	Marble (Zhang et al. 2009)	87.56		105.65	
	Limestone (Zhang et al. 2009)	123.97		91.46	
	Sandstone (Zhang et al. 2009)	170.98		163.52	
	Granite (Xu and Liu 2000)	185	163		173
	Shale (Masri et al. 2014)	39.67		35.41	30.97
Elastic modulus E (GPa)	Marble (Zhang et al. 2009)	17.73		19.69	
	Limestone (Zhang et al. 2009)	17.77		17.03	
	Sandstone (Zhang et al. 2009)	16.73		17.77	
	Granite (Xu and Liu 2000)	83	95		88
	Shale (Masri et al. 2014)	19.5		18	14.5

nuclear waste, for which the temperature was often above 800°C. It was found that for some rocks the strength and the elastic modulus were reduced but for others they were increased with an increase of temperature from 20°C to 150°C (Zhang et al. 2009; Xu and Liu 2000; Masri et al. 2014), as shown in Table 1, the thermal effects on mechanical properties are not the same for granite, marble, limestone, sandstone, and shale between 20°C and 150°C.

Slate is a typical rock, on which many uniaxial tests, conventional triaxial compression tests and rheological tests have been performed at room temperature (Mao and Yang 2005; Mao et al. 2006; Li et al. 2012; Gholami and Rasouli 2014). So far no tests for slate have been performed at elevated temperatures and pressures, and it is expected that the thermal effects between 20 °C to 150 °C on the mechanical characteristics are not comparable between granite, marble, limestone, sandstone on the one hand, and shale on the other hand.

The main research question of present study was to determine the mechanical characteristics of slate rocks up to a temperature of 120°C. Therefore, conventional triaxial compression tests on slates at different temperatures up to 120°C were carried out. Emphasis was given to the characterization of thermal effects on the deformation modulus and the compressive strength of slate. The thermal effects on mechanical characteristics of slates could be revealed. The results of present study will provide input data for detailed numerical analysis of the stability of tunnel excavations.

1 Methodology and Testing Scheme

All the slate samples tested were taken from a railway tunnel with 1400 meters overburden. The slate samples are kept at their in situ moisture content. The cylindrical samples were 50 mm in diameter and 100 mm in height, their top and bottom were polished to flatness of 0.02 mm and their heights were accurate to ±1 mm. The samples were taken in the direction perpendicular to the bedding plane of the slate.

Figure 1 MTS 815.03 triaxial test equipment. (a) Total view; (b) The equipment used to measure lateral and axial deformation; (c) The arrangement for heating and keeping at constant temperature of the samples.

The MTS815 triaxial apparatus (Figure 1), produced in the U.S.A., was used for these tests. It can apply a maximum temperature of 200°C and a confining pressure of up to 140 MPa. A data logging system and a micro-computer were used to record the test data. The axial displacement was measured by a pair of linear variable differential transformers (LVDTs) which were located on the samples; the lateral strain of the samples was measured using a specially designed ring, as shown in Figure 1b. The test scheme for the 20 slate samples is shown in Table 2. Five confining pressures (5, 10, 15, 20 and 25 MPa) and four values of temperature (20°C, 40°C, 80°C and 120°C) were applied.

The tests were undrained and the loading procedure was as shown in Figure 2.

(1) The sample is positioned according to the requirements of the triaxial testing machine.

Table 2 Dimensions and testing conditions of the slate samples

Sample No.	Diameter (mm)	Length (mm)	Temp. (°C)	Confining pressure (MPa)
S-20-1	49.35	101.28	20	5
S-20-2	50.52	102.26	20	10
S-20-3	49.99	101.35	20	15
S-20-4	50.26	101.66	20	20
S-20-5	50.94	102.15	20	25
S-40-1	49.59	100.31	40	5
S-40-2	49.99	100.54	40	10
S-40-3	50.34	100.7	40	15
S-40-4	49.91	100.25	40	20
S-40-5	50.22	100.37	40	25
S-80-1	51.9	101.32	80	5
S-80-2	50.85	97.51	80	10
S-80-3	50.18	99.46	80	15
S-80-4	50.32	100.21	80	20
S-80-5	50.11	101.46	80	25
S-120-1	49.81	101.63	120	5
S-120-2	49.89	101.25	120	10
S-120-3	50.02	100.38	120	15
S-120-4	51.53	101.76	120	20
S-120-5	48.63	100.07	120	25

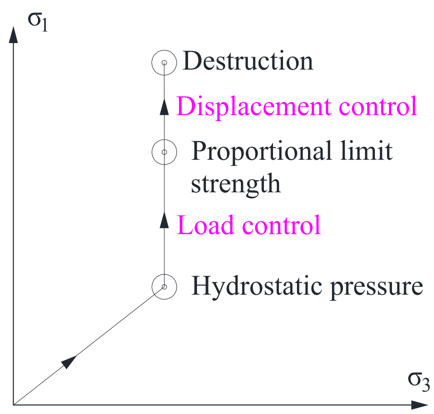


Figure 2 Sketch of the stress path applied during the triaxial tests.

(2) The sample is heated to the desired temperature at a rate of 2°C/min and maintained at a constant temperature for 5 hours before testing (Figure 1c).

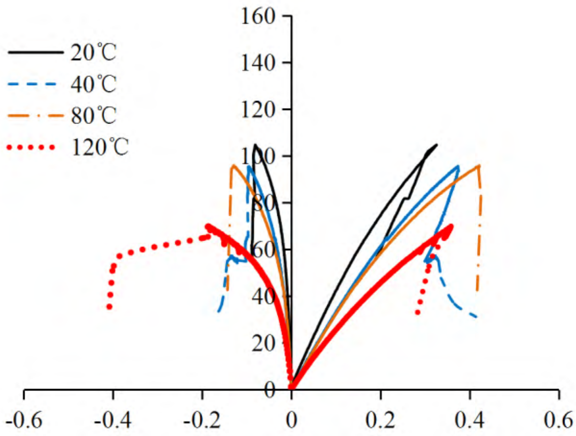
(3) The confining pressure is applied to the desired values at a constant rate of 5 MPa/min.

(4) The axial force on the sample is increased with a rate of 30 kN/min up to the value of the rock proportional limit strength (70% of the peak strength). From then the loading was deformation controlled at a rate of 0.02 mm/min, until failure.

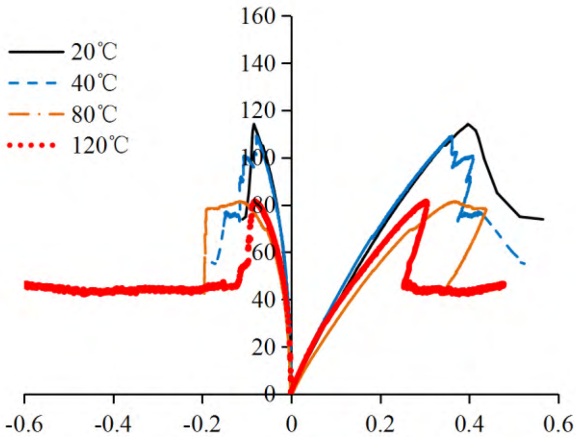
2 Main Results and Discussions

The stress-strain curves of all tests are shown in Figure 3. The deformational behavior of the samples can be subdivided into three phases: elastic deformation, the yield phase and the failure phase. During the elastic deformation phase, the axial and lateral strains increase linearly, and the axial strain is much larger than the lateral strain. During the yield phase, the axial and lateral strain both increase and deviate from the straight line. During the failure phase, the stress significantly decreases and the strain significantly increased.

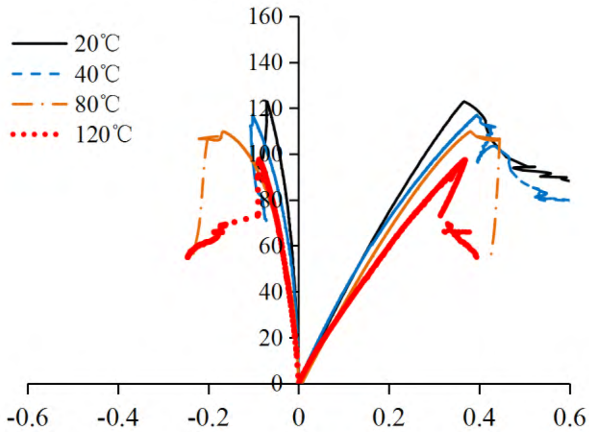
Figure 3 shows that an increase of confining pressure significantly affects the mechanical properties of slate. The peak strength increases with the increase of confining pressure from 5 to 25 MPa for the same temperature. The effect of confining pressure on the strength characteristics of the slate was discussed, the present test results at room temperature was compared with those given by Mao et al. (2006), a comparable effect for the confining pressure effect had been found. In both cases the peak strength increases significantly with increasing values of confining pressure. The peak strength decreases in present tests with increasing temperatures at constant values of confining pressure. This thermal effect has also been observed on granite (Xu and Liu 2000), marble (Zhu et al. 2007) and shale (Masri et al. 2014). The deformational behavior of slate becomes slightly more ductile under higher values of temperature leading to an increase of the deformation at the same values of confining stress. It is concluded that the heating leads to a significant reduction of the peak strength but enhances the deformability and ductility of slate.



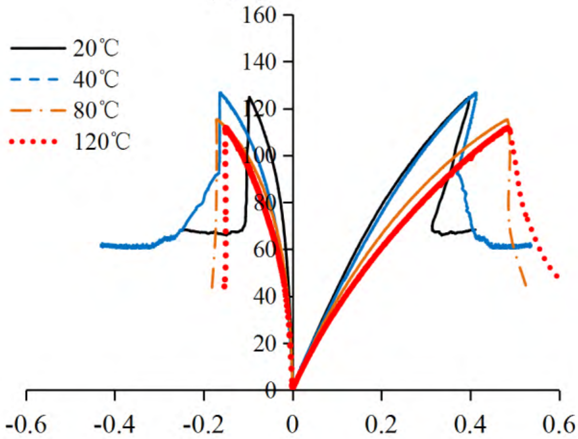
(a) σ_3 = 5 MPa



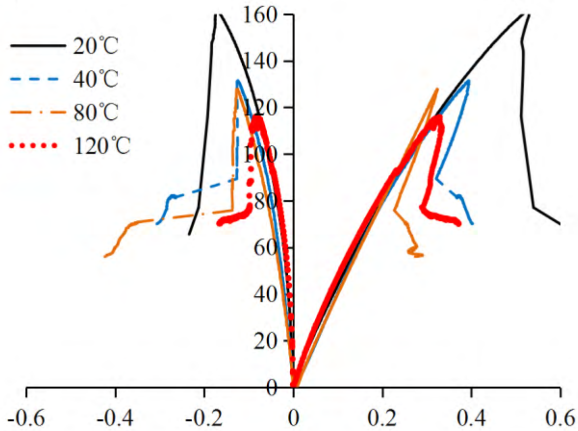
(b) σ_3 = 10 MPa



(c) σ_3 = 15 MPa



(d) σ_3 = 20 MPa



(e) σ_3 = 25 MPa

Figure 3 Stress-strain curves at different levels of confining stress and temperature.

Further we observed that at the confining pressure of 25 MPa the axial strain is almost equal for the four different values of temperature (Figure 3e), however, at the confining pressure of 5MPa it is significantly different (Figure 3a), so at higher values of confining pressures the thermal effect on rock deformation characteristics decreases.

In order to further examine the temperature effects on the deformational behavior of slate, we present in Table 3 the experimental values of peak strength, elastic modulus, Poisson's ratio, cohesion and friction angle calculated from the triaxial compression tests. The relationship between the peak strength and the temperature is shown in Figure 4. The average value of the peak strengths at 20°C for the 4 values of confining pressure, decreases by 7.7% (for 40°C), 15.5% (for 80°C) and 23.4% (for 120°C) at higher temperatures. This nonlinear relationship between the average values of peak strength and the temperature in our tests can be expressed as:

$$\sigma_1 - \sigma_3 = 0.00117T^2 - 0.4405T + 133.2 (R^2 = 0.9927) \quad (1)$$

The failure stresses of present tests were compared with those given by Masri et al. (2014), higher temperature can lead to a decrease of the failure stress, and it was observed that there is a good accordance with their results. The relationship between $(\sigma_1 - \sigma_3)/2$ and $(\sigma_1 + \sigma_3)/2$ based on the values of peak stress and confining pressure of present tests at 4 different temperatures is shown in Figure 5. This shows that these relationships are nearly linear with a strong dependency on $(\sigma_1 + \sigma_3)/2$.

Linear Mohr–Coulomb strength criteria was used to represent strength behavior, the values for cohesion (C) and friction angle (φ) at the four levels of temperature are shown in Figure 6. At higher temperatures the shear strength of the slate decreases due to a significant decrease of cohesion. The friction angle is hardly affected by increasing temperature. Higher temperatures lead to the expansion of the mineral grains and growing of cracks, and the distance between molecules increases, which will effectively reduce the cohesion. However, the friction angle is a surface property of the material which shouldn't be affected by the increase of temperature, so the variation in friction angle is almost negligible.

To determine the effects of temperature on the deformation behavior, the elastic modulus (E_{50}) and the Poisson's ratio (μ_{50}) of the slate samples have been calculated at different values of temperature from the stress–strain curves (Gao et al. 2005), as shown in Table 3.

$$\mu_{50} = \frac{\frac{\varepsilon_3}{\varepsilon_1}\sigma_1 - \sigma_3}{\left(2\frac{\varepsilon_3}{\varepsilon_1} - 1\right)\sigma_3 - \sigma_1} \quad (2)$$

$$E_{50} = \frac{\sigma_1 - 2\mu_{50}\sigma_3}{\varepsilon_1} \quad (3)$$

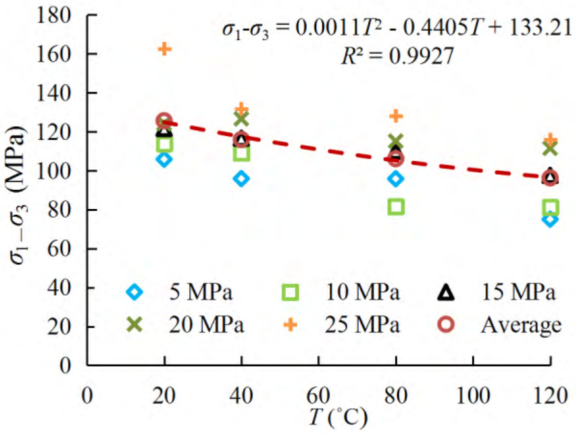


Figure 4 Relationship between the peak strength and temperature at the 5 different levels of confining pressure.

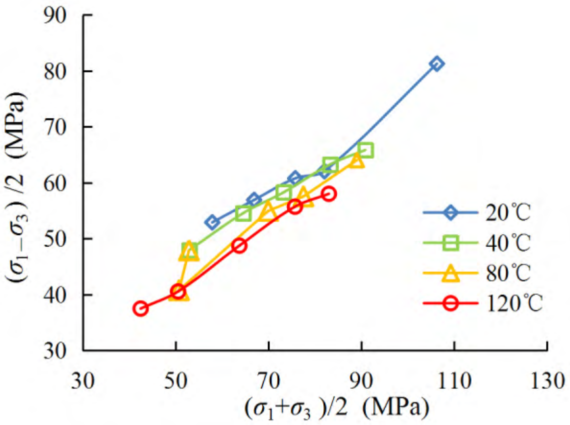


Figure 5 Curves of $(\sigma_1 - \sigma_3)/2$ against $(\sigma_1 + \sigma_3)/2$ for the four different levels of temperature.

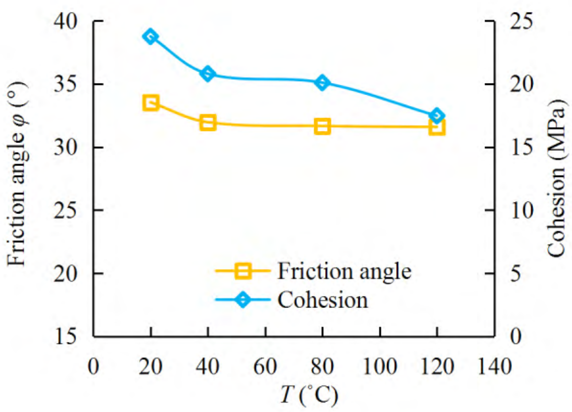


Figure 6 Relationship between the shear strength parameters and temperature (T) of the slate in triaxial compression.

where μ_{50} is the Poisson's ratio at half of the peak strength, E_{50} is the secant modulus of elasticity at half of the peak strength, σ_1 is the axial stress, ε_1 is the axial strain, σ_3 is the confining pressure, and ε_3 is the lateral strain.

Effects of temperature on the elastic modulus can be found in Figure 7. The elastic modulus decreases at higher temperatures, the thermal effect on elastic modulus is different from granite, the elastic modulus of granite is increased with increasing temperature before 75°C (Xu and Liu 2000), which may be due to the different kind of mineralogy. The average value for the elastic modulus of the samples is 43.4, 41.3, 37.1, 37.6GPa at 20°C, 40°C, 80°C, 120°C, respectively. Compared to the average value of the elastic modulus at 20°C, the average value of the elastic modulus decreased by 4.9% (40°C), 14.4% (80°C) and 13.7% (120°C), respectively. The decrease of the elastic modulus with increasing temperature is lower than the decrease of peak strength, which is reduced by 23.4% at 120°C (Figure 4). This means that the thermal effect on the elastic modulus is relatively smaller than on the peak strength.

The differences between the values for peak strength and elastic modulus at the different levels of confining pressure are larger at higher temperatures than at lower temperatures (Figures 4 and 7). At 20°C, the axial stress - strain curves are nearly similar for the different values of confining stress (Figure 8a). At 120°C, the stiffness increases significantly with an increase in confining pressure (Figure 8b). The peak strength, elastic modulus and Poisson's ratio increase with increasing confining pressure, which are the effects of confining pressure on rock mechanical behavior. According to Figures 4, 7 and 8, the effects of confining pressure are larger significantly at higher temperatures than at lower temperatures, which means that at higher temperatures the effects of confining pressure on rock mechanical behavior is enhanced.

The Poisson's ratio μ_{50} is the ratio between the lateral and axial strains at half of the peak strength; the lateral strain is measured using a circular (circumferential) ring (Figure 1b). The Poisson's ratio increases with higher values of temperature and confining pressure (Figure 9). The average values of the Poisson's ratios at different confining pressures are 0.242, 0.272, 0.292 and 0.294 at 20°C, 40°C, 80°C, 120°C, respectively. As compared to the Poisson's ratio at 20°C, the average Poisson's ratio increases by 12.6% (40°C), 20.5% (80°C) and 21.5% (120°C), respectively. This means that the thermal effect on the Poisson's ratio

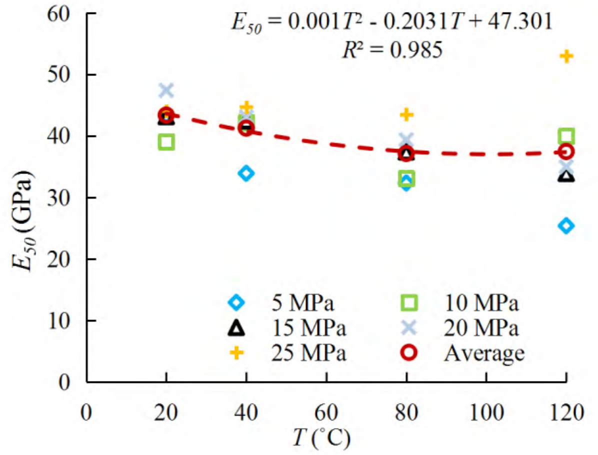


Figure 7 Relationship between the elastic modulus (E_{50}) and temperature (T) at the five different levels of confining pressure.

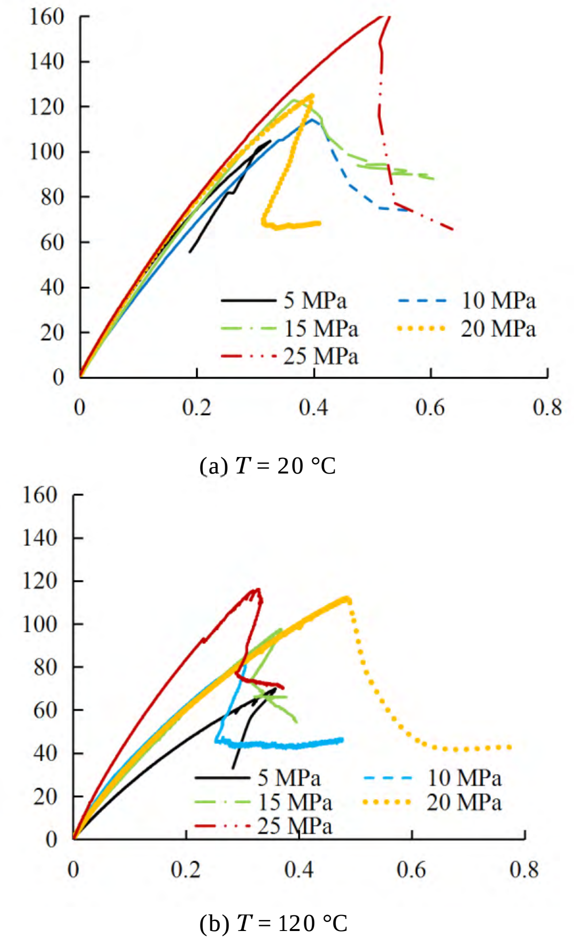


Figure 8 Stress - axial strain curves at the five levels of confining pressures at the temperatures of 20°C and 120°C.

is relatively smaller than on the peak strength, and larger than on the elastic modulus.

There are different types of mineral present in the slate specimen and their thermal coefficients are unequal, thus different deformation and thermal stress levels are generated in the slate specimen by increasing temperature. Existing cracks will be widened and become connected, and new micro cracks will appear due to thermal stress. This explains the reduction of the strength properties of the slates such as the peak strength, elastic modulus and the increase of the Poisson's ratio with rising temperatures (Figures 4, 7 and 9).

Some examples of failure patterns of the slate samples at different temperatures but at low confining pressure are shown in Figure 10. In general, the slate samples fail in shear failure, the failure surface is a shear plane.

3 Conclusions

The following conclusions from conventional triaxial compression tests at different temperatures on cylindrical samples of slates can be drawn:

(1) High confining pressures weaken the thermal effects on rock mechanical characteristics while higher temperatures enhance the effect of confining pressure.

(2) The mechanical behavior of slate rock material is significantly affected by the temperature. Higher temperatures lead to a decrease of the peak strength but to an increase of the deformability and ductility of the slate. The peak strength and the elastic modulus decreases and the Poisson's ratio increases with increasing temperatures. The thermal effect on the peak strength and Poisson's ratio is larger than on the elastic modulus.

(3) The slate's mechanical properties show a strong dependency on the level of the confining pressure. The peak strength, elastic modulus and Poisson's ratio increase with increasing confining pressure. The effect of confining pressure on the peak strength and Poisson's ratio is relatively larger than on the elastic modulus.

(4) Higher temperatures reduce the shear strength of slate, the decrease is mainly caused by a decrease of the cohesion; the reduction in friction angle is almost negligible, the failure of slate

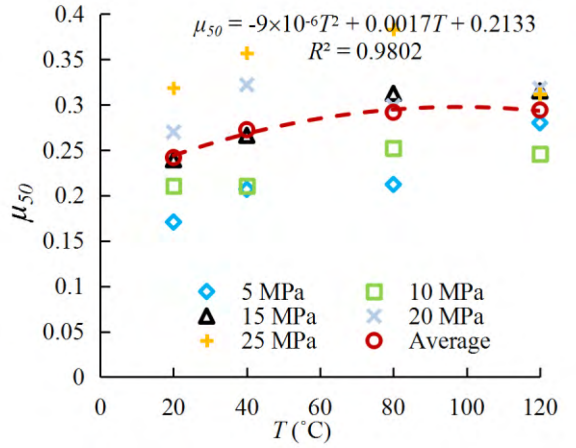


Figure 9 Relationship between the Poisson's ratio (μ_{50}) and temperature (T) at the 5 different levels of confining pressure.

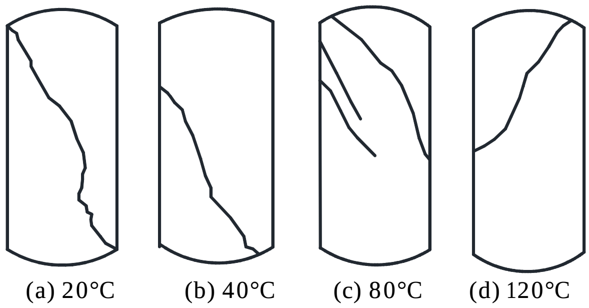


Figure 10 Examples of failure planes in the tested slate samples (σ_3 = 5 MPa).

samples is characterized by a shear plane.

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