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Strength and post-peak response of Colorado shale at high pressure and temperature

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ABSTRACT

The paper presents the thermo-mechanical strength characterization of Colorado shale which serves as a cap rock to underlying oil-rich formations in Cold Lake area, east-central Alberta, Canada. Samples from the Westgate and Joli Fou formations were tested at high temperatures along triaxial compression stress paths with effective consolidation pressures and temperatures consistent with in-situ stresses and operative conditions. These lab tests were complemented with indirect tensile strength, unconfined compression and triaxial constant effective mean stress tests at ambient temperature for a more comprehensive knowledge of the material strength, particularly, at low confining pressures. The lab experimental results revealed brittle behavior of the tested shales with considerable strain softening. Both peak and post-peak strength envelopes of the tested material were observed to be nonlinear with a pronounced curvature at low mean stresses and to decrease at high temperatures. A simple thermo-mechanical failure criterion is proposed to capture the aforementioned constitutive features. This provides a modeling framework for determining the material strength close to the zone of tensile failure at different temperatures which is of utmost relevance to cap rock integrity assessments. Finally, measured axial and radial deformations as well as X-ray tomography images were used to verify that the observed constant rate of dilation in the post-peak response of the samples was a reflection of the morphology of the virtually smooth shear plane, and not representative of the material behavior.

1. Introduction

A detailed knowledge of the thermo-hydro-mechanical behavior and strength of shale is essential in the safe design and operation of heavy oil extraction processes such as Steam Assisted Gravity Drainage (SAGD).[1] In such a process, the injection of steam at high pressures into the reservoir formation induces high excess pore fluid pressures and thermo-mechanical stresses into the overlying shale cap rock which can potentially lead to material failure. As such, the integrity of the shale cap rock which plays the role of a hydraulic seal to the injected fluid in SAGD process is compromised.

Shale usually possesses an initial transversely isotropic structure and its mechanical behavior is typically influenced by both effective confining pressure and temperature, see e.g. Refs. 2–5. As a common trend, an increase in effective confining pressure leads to a higher strength and stiffness of the shale.[6] On the contrary, temperature-induced variations in the strength of shales and clayey soils do not follow a consistent trend at elevated temperatures, see Ref. 7 for a comprehensive review of the corresponding experimental studies.

For clayey soils, numerous experimental studies show that elevated temperatures may degrade or enhance their strength, e.g. see Refs. 8–12. This variety in thermal strength response can be partly explained with regard to the mineralogical composition and initial thermodynamic state of the tested samples, as well as the mechanical and thermal loading paths to reach this state. Drainage conditions during heating in addition to the thermal and mechanical consolidation history have been reported as the chief factors to affect the thermo-mechanical strength of clays.[10,13,14] At the microscopic scale, several factors that contribute to macroscopic strength can be identified, namely, enhanced mobility of interlamellar water and the consequent change in the density of clay stacks,[15] reduced strength of interparticle contacts and formation of a new soil fabric,[16] increased number of solid–solid contacts due to the lower strength of the adsorbed water[10] as well as clay mineralogy, and physico-chemical changes at elevated temperatures.[17]

In the case of shale, the shear strength has been mostly reported to decrease at elevated temperatures, except for a few cases where the opposite trend was observed. For instance, Kosar[18]

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Table 1
Physical properties of the tested shales.

Formation	Tube no.	Depth (m)	w_n (%)	G_s	PL (%)	LL (%)	OC (%)
Westgate	75	245.1–246.6	17	2.735	32	64	2
Westgate	77	248.1–249.6	18	2.742	43	88	2
Joli Fou	114	299.3–300.8	17	2.751	33	59	2
–	–	Standard procedure	ASTM D 2216	ASTM D 845	ASTM D 4318	ASTM D 4318	ASTM D 2974

Note: w_n is the natural water content, G_s is the specific gravity, PL is the plastic limit, LL is the liquid limit and OC is the organic content.

showed that the shear strength of Clearwater formation shale, Alberta, Canada, increased at higher temperatures based on drained triaxial compression tests at two temperatures, 20 and 225 °C. The opposite trend was reported by Ibanez and Kronenberg[4] for Wilcox shale from West Louisiana at temperatures between 22 and 196 °C. Chalaturnyk[19] conducted triaxial compression tests on upper and lower McMurray shales, a mixture of shale and oil-sand, at 20 and 225 °C. The results showed a decrease and an increase of strength with temperature for Upper and Lower McMurray shales, respectively. Undrained triaxial compression test results published by Okada[20] on mudstone at 20 and 60 °C, also verified a decreasing trend in shear strength. Moustafa et al.[5] performed a comprehensive set of drained triaxial compression tests on Tournemire shale at five different temperatures between 20 and 250 °C, which also revealed weakening of the samples at elevated temperatures.

It appears from previous studies reported in the above-mentioned literature that there are inconsistencies in the characterization of the thermo-mechanical strength of clays and shales. Given the importance of shale behavior on the safe and economical extraction of heavy oil in SAGD process, the present study aims at addressing in detail the effects of temperature on the strength of Westgate and Joli Fou shales obtained from the Colorado group in Cold Lake area, east-central Alberta, Canada. The main objective is to study the thermo-mechanical strength by conducting a series of triaxial tests at different effective consolidation pressures, temperatures and stress paths. One of the outcomes of this study is a thermo-mechanical failure criterion derived from the analysis of the lab experimental results. Characteristics of post-peak response of shale in the form of localized deformations are also discussed in order to provide insights for a subsequent development of a proper thermo-mechanical constitutive model for shales.

2. Tested material

The samples used in this study were obtained from the Cold Lake area whose stratigraphy includes the Manville group as the major source of bitumen overlain by Colorado group which serves as a natural cap rock to prevent vertical propagation of steam chamber in the SAGD process. Conventional double-barrel coring technique was performed in the vertical direction, direction of material deposition, to recover cores from Westgate and Joli Fou formations which extend from 236 to 283 m and 301 to 322 m below the ground, respectively. Both formations were deposited in the Cretaceous Interior Seaway with a generally uniform appearance dominated by gray to dark gray mudstone/shale.[21] In the field, cores were carefully cut into 1.5 m segments, sealed with heat shrinkable membranes and especially preserved in PVC tubes in order to avoid loss of moisture content and to minimize mechanical disturbance. Later on, quality assessment of the preserved cores in the laboratory using the X-ray Computed Tomography (CT) technique verified that the preservation procedure had been indeed quite successful.

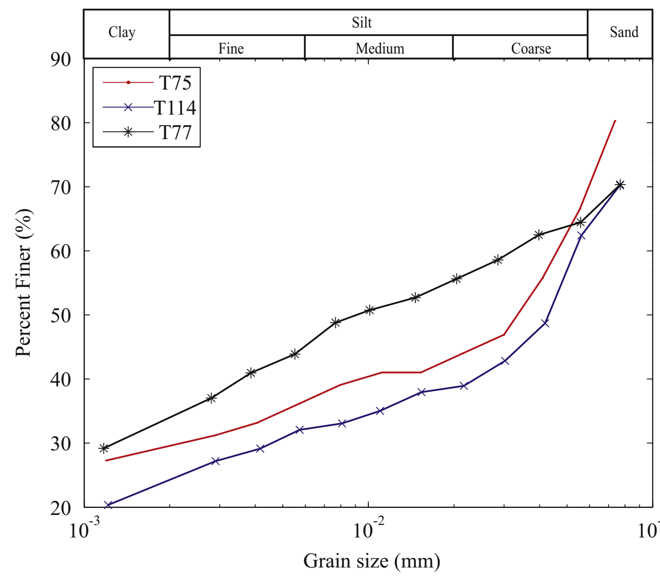

Fig. 1. Particle size distribution of the Westgate and Joli Fou shale samples.

Triaxial test specimens were chosen from tubes T75, T77 and T114 whose formations and depths are given in Table 1. The range of bulk density and porosity of core samples as obtained from well logs are 2150–2230 kg/m^3 and 0.32–0.34, respectively. At least two samples were chosen from each tube for determination of index properties (average natural water content, specific gravity, plastic limit, liquid limit and organic content), the results of which are also reported in Table 1. Following ASTM D 422[22] hydrometer analysis was used to determine the particle size distribution of the samples as displayed in Fig. 1. It can be observed that silt-sized particles are dominant in the grain size distribution curves while clay-sized particles are estimated to constitute approximately 25–35% of the samples.

Scanning Electron Microscope (SEM) imaging was used to investigate the composition and initial microstructure of the samples. Two types of imaging modes were used, namely imaging with back-scattered electrons (BSE) and imaging with secondary electrons (SE). Images of the former mode provide elemental composition information about the sample while those of the latter mode are used to obtain information about morphology and surface topography of the samples. Fig. 2a illustrates an image of sample T77S2, see Table 2, in BSE mode at 10 µm resolution, where brighter spots show elements with higher atomic numbers. Comparison of the image with a comprehensive library of the elements, showed existence of pyrite clusters, Fig. 2b, organic materials as well as abundant clay minerals in the sample. SE mode images of the same sample (T77S2), as demonstrated at 4 and 10 µm scales in Fig. 2c and d, respectively, show that clay platelets have dominant face-to-face contacts parallel to the