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Fracturing in the Oil-Sands Reservoirs

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Abstract

Based on its deformation properties, Alberta oilsands reservoir material is classified as an interlocked sands. It possesses relatively high initial friction strength and exhibits a significant dilation tendency once it is shear-mobilized. How does such a medium behave under high injection pressures? Using analytical derivations and numerical simulations, this paper illustrates the evolving shear-induced failure and tensile-dominated fracturing behavior in the oilsands. It concludes that the fracturing process is a combination of shear dilation and tensile parting at micro scales. Laboratory and field data exist to support the theoretical observations. Finally, a discussion will be given about impact of such fracturing behavior on the reservoir engineering processes. It will shed light on proactive utilization of the dilation for the in-situ oilsands development.

Introduction

The oilsands reservoirs need stimulation. Aiming at reducing the oil viscosity, the stimulation injects steam and/or solvent which will be referred to as "stimulants" collectively. In order for the stimulation to be effective, the stimulants must be first placed in the reservoir at the target time and/or place. By far, hydraulically-induced fracturing is the most effective means of injecting stimulants into the reservoir. Therefore, fracturing of the oilsands reservoir is a fundamentally important to the reservoir engineering.

On the other hand, fracturing of the oilsands is a serious topic among stakeholders concerned about the caprock integrity. While our industry strives to be responsible and proactive in protecting the environment hydraulic fracturing involves high injection pressures and may appear contrary to preserving the caprock integrity. In this case, a good understanding of the fracturing process can enable us to be proactive --- no fear and meanwhile, no ignorance. Only by arming ourselves with adequate knowledge can we become proactive.

In the petroleum industry, a fracture in the subsurface rock formations is generally perceived as a linear feature with two planes separated by a certain aperture between. Sometimes, it is referred to as a "parallel-plate fracture model". In this paper, we will show that the fracturing process in the oilsands actually causes a zone of a concentrated high porosity. This zone has a much wider thickness compared to the commonly-perceived linear fractures. The rock matrix is mostly continuous inside the zone. The high porosity comes mostly from shear-induced dilation and to an extent, from tensile parting. In simple terms, the dilated rock still has sand grains in contact while the tensile parting has the grains detached from each other. The tensile parting in the high-porosity zone causes only micro-cracks. These cracks do not extend far and do not connect with each other. Between the cracks there is still continuous dilated rock matrix continuum. Therefore, the fracture in the oilsands is different from the parallel-plate fracture model.

The following description will use analytical and numerical simulations as well as field data to support our arguments. First, some published laboratory test data are used to illustrate the significant dilation tendency of the oilsands and discuss its associated flow-deformation coupling effect. Then, analytical derivations are given on initiation of failure around a circular opening. In the third section, geomechanical simulation evidence is introduced to illustrate progression of the failure under continuing high-pressure injection. In the fourth section, field data from mini-frac tests and other relevant field tests are presented to further illustrate the fracturing process in the oilsands. References, figures and tables are left to the end of this paper. In this paper, failure and fracturing are used interchangeably unless otherwise distinguished from each other.

Fracturing Behavior in Oilsands --- Dilation and Flow-Deformation Coupling

This section presents laboratory evidence of the significant dilation tendency in the oilsands based on literature review. Analytical derivations are given to illustrate the impact of the dilation in increasing the porosity and then effective water mobility. The subject of fracturing behavior of the oilsands has attracted significant attention from the industry and academia alike. Due to the limitation in space, the review here can only focus on representative historical works and is not meant to be exclusive. Many works will not be mentioned here, however, this is not meant to discredit these works.

Earlier works on mechanical properties of the oil sands aimed at studying slope stability for open-pit mining in the oil sands formations. Load-bearing capacity of the oil sands to support mining equipment was also one of the study indices. Therefore, attention was mainly focused on the shear strength of the oil sands, such as in works by Hardy and Hemstock (1963). The works were cumulated in Dusseault (1977). A significant portion of the results was published in Dusseault and Morgenstein (1977 and 1979). Unusually high shear strength and highly dilative behaviour at low confining pressures were discovered. Origin of the high strength was attributed to the inter-penetrative fabric structure of the oil sands. Further works on the fabric structure and its influence on the strength of the oil sands were reported in Barnes (1980), and Barnes and Dusseault (1981).

More recent works on mechanical properties of the oil sands expanded their focus to include deformation behaviour. Temperature effect or mechanical properties of the related strata other than the oil sands payzone were also tested. These works included Agar (1984), Kosar (1989) and Wong et al. (1993). The most recent works by Samieh (1995) and Wong (1999) represent state of the art geomechanical tests on the oil sands. These works used more advanced test procedures to reduce end effects of the samples so that deformation was more homogeneous inside the sample. The tests were conducted at low confining pressures less than 750 kPa on the Athabasca oil sands. Significant dilation tendency was observed under such low confining pressure environment.

Some key observations relevant to the context of this paper are summarized below:

(1) The oil sands was identified as behaving like a dense sands mechanically, but its grain contacts have been altered from the typical tangential type to an interpenetrative nature. A large number of grain contacts in the oil sands exhibit long and concavo-convex nature, resulting in an even larger contact area (Dusseault, 1977; Dusseault and Morgenstein, 1977; Dusseault and Morgenstern, 1979; Barnes, 1980; Barnes and Dusseault, 1981).

(2) The tangential contact is a direct result of deposition and compaction. Alteration from the tangential to the interpenetrative contact in the oil sands is caused by diagenetic processes after the deposition. To certain degrees, pressure solution and crystal overgrowth occurred. Glaciation is the main factor responsible. It was reported that the recent glacial ice sheet was as thick as 2 to 3 kilometers (e.g., Clark, 1980). This is equivalent to a minimum of 20 to 30 MPa of vertical overburden weight that was once exerted on the top of the oilsands formation. Its impact can be far-reaching.

(3) In general, there are two unique characteristics associated with the deformation of dense sands at low confining pressures: strain softening and dilation. This is true for the oilsands. Furthermore, its interpenetrative fabric structure causes an unusually high friction angle and high dilative propensity once it is shear-mobilized at low confining stresses (e.g., Dusseault and Morgenstein, 1977; Barnes and Dusseault, 1981; Samieh, 1995; Wong, 1999).

The above-described laboratory tests were done on McMurray, Grand Rapids and Clearwater sandstone formations. One can infer that similar observations can be extended to other formations such as Wabiskaw sands which was seldom tested. The unique grain-grain contact structure in the oilsands is responsible for its significant dilation tendency. Such micro-structure resulted from historical glaciation. Influence of the glacial activities should extend to all the formations in the region.

In a mean stress (p') vs. Mises stress (q) diagram, Figure 1 summarizes various stress measures from Samieh's low-pressure tests (Samieh, 1995). "Peak" refers to the highest axial stress level each sample experienced in the triaxial tests. "Residual" is the final stress level at the end of the tests. "Average" is the average between the peak and residual strengths. "Plastic yielding" is the deviation point from the initial elastic straight line. These strength data can be fitted to a linear Drucker-Prager (DP) strength criterion below:

$$q = p'\tan(\beta) + c \qquad (1)$$

The corresponding DP parameters, i.e., friction angle (β) and cohesion (c), are summarized in Table 1. Therefore, the DP friction angle for the plastic yielding can be as high as 62º and the associated cohesion is 62 kPa.

Corresponding to the high friction angle, the oilsands material exhibits a high dilation tendency. For example, in one of the laboratory tests described above, the volumetric dilative strain reached 6% at the end of the tests after the sample had undergone an axial strain of 7% (Figure 2). This yields a dilation angle at 48º and denotes the dilation tendency during the early stage of the plastic deformation. The volumetric strain rate decelerates during the late stage of the test (Figure 2) which is likely caused by the end effects during the tests. The shear planes formed during the early stage of the test correspond to the initial high dilation angle and reach close to the sample ends. The friction between the sample and loading platen restricts the further development of sliding along the shear planes, thus resulting in a smaller dilation tendency towards the end of the tests.

Impact of the high dilation tendency in the oilsands is significant in terms of enhancing its effective water mobility. The oilsands is water-wet. Most of them has essentially no or a very small initial mobile water saturation. Therefore, the initial relative permeability to water can be near zero or very small. After the dilation, porosity increases space is occupied by the injected water. As a result, the water saturation increases as well as the water and water mobility.. The following analysis further illustrates that the increase in relative more significant than that from the absolute permeability increase due to the increased porosity.