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Some Aspects of Athabasca Oil Sand Behavior, Alberta, Canada

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Abstract. The basic behavior of Athabasca oil sand under uniaxial loading may be expressed as a property of both elastic and viscous bodies, where the predominance of each component depends on its composition.

Cyclic loading deformations showed that the shear strength of oil sand is almost half those of a static load, probably because of dissipation of energy and increase in temperature. However, a cyclic load with a previously applied static load, destroys the shear strength of oil sand, probably due to its structural viscosity.

Oil sand under hydrostatic pressure has a viscous deformation. The rate of deformation is a function of the bitumen viscosity. The bitumen viscosity greatly depends on the temperature, and so does the rate of deformation.

The represented investigations on disturbed (remoulded) samples without a gaseous phase, are intended to show the unique property of oil sand. However, a definite evaluation of the behavior of oil sand can be done only on intact of undisturbed deposits in the field.

Key words: Oil sand – Composition – Properties – Behavior – Structural deformation.

Introduction

The Lower Cretaceous sands, silts, and shales of the McMurray Formation lie unconformably on Devonian limestone and are overlain disconformably by marine shales of the Lower Cretaceous Clearwater Formation. Some time after the deposition of the McMurray Formation the bitumen probably migrated into waterwet sands (Hardy and Hemstock, 1963). The thickness of the oil sand formation varies between 6 and 60 m. It is covered by overlying strata up to 1300 m thick, some of which were later eroded. The present ground surface is the result of Pleistocene glaciation and recent erosion. The oil sand formation gently dips from its exposure at the Athabasca River to the east

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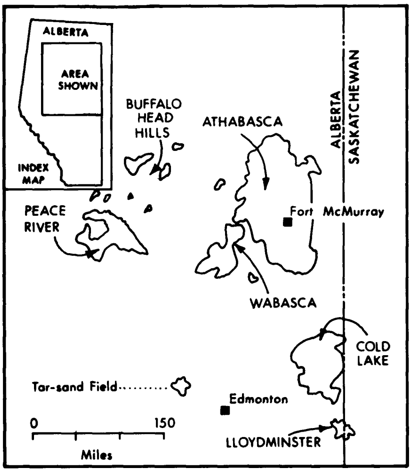

Fig. 1. Alberta's oil sand deposits

and west, where it is covered by up to 1300 m of overburden. The Athabasca oil sand deposit is the largest one (Fig. 1) in the province of Alberta.

Current estimates are that all oil sands deposits in Alberta contain about 700 billion bbl of crude oil (McConville, 1975). This is roughly equivalent to ten times that of the combined U.S.A. and Canadian total oil reserves. It is obvious that oil sand deposits are one of the more important sources of energy. At present the only developed method for oil sand exploitation is open-pit mining. By this method 10 percent of the total bitumen reserves can be obtained (pit limit 60 m of overburden). However, at present very intensive research work is in progress for "in situ" bitumen recovery. This method may perhaps be applied where the thickness of overlying strata exceeds 200–300 m. For this part of the oil sand deposits it is necessary to find some subsurface exploitation system or systems which might be applicable, for large scale production.

The oil sand has an unique composition as a four-phase system: solid-sand, viscous-bitumen, gaseous, liquid-water. This medium represents an enigma to develop some efficient mining system for subsurface production either of oil sand or just bitumen (Jeremic, 1975). It is obvious that the behavior of oil sand at depth is different from that at the surface or near the surface. The intention of this work is to point out those differences, and for this reason laboratory investigations of oil sand properties have been carried out. For uniaxial loading an Instron testing system (TT-D) has been used, and for triaxial loading, a triaxial cell (Soiltest) loaded by Instron an improvised apparatus for lateral pressure. All tests have been conducted in the laboratories of the Department of Mineral Engineering, the University of Alberta, Edmonton. The oil sand property delineated in this representation should be considered as preliminary because the testing has been done on disturbed (remoulded) samples without a gaseous phase. A definite evaluation of the behavior of an oil sand deposit can be done only by testing within an underground opening.

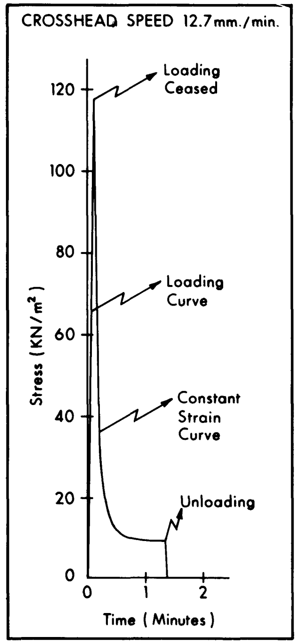

Fig. 2. Oil sand deformation at high speed of loading (high grade ore, room temperature)

Deformations as a Function of the Speed of Loading

Investigations of oil sand samples under unconfined pressure (Instron) at various constant crosshead speeds, and at various mixture composition showed their basic properties. Tests have been carried out on cylindrical samples (diameter – 43.7 mm) of remoulded oil sand. They have been compacted in layers to obtain densities in the range of 2 g/cm^3.

The behavior of oil sand as a function of the high speed load mechanism is illustrated in Figure 2. The strain-rate sensitivity of the stress, at constant crosshead speed of 12.7 mm per minute shows the following deformation characteristics:

1. The loading deformation curve is instantaneous, and very steep.
2. when the cross head displacement was stopped, the sample relaxed and the relaxation was rapid.
3. After the load was removed, the curve dropped instantly to zero (like a spring release).

The behavior of oil sand as a function of the low speed load mechanism is illustrated in Figure 3. The strain-rate sensitivity of the stress, at constant crosshead speed of 0.127 mm per minute shows the following deformation characteristics:

1. The loading deformation curve is linear with a low slope.
2. When the crosshead displacement was stopped, the deformation continued and stress decreased.

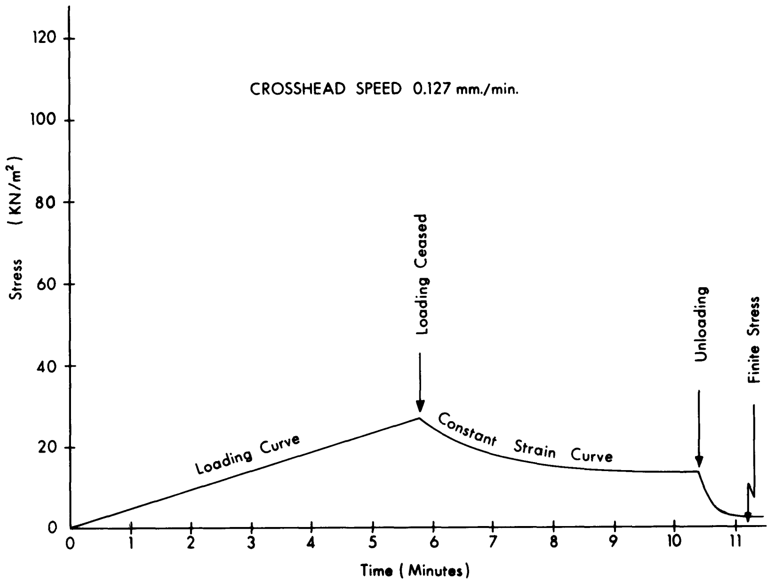

Fig. 3. Oil sand deformation at low speed of loading (high grade ore; room temperature)

3. After the load was removed the deformation curve declined to a certain point and became constant (similar to dashpot deformation).

Both tests show that oil sand may have the properties of two individual elements: elastic (spring) and viscous (dashpot). These two elements in its composition may control the basic deformation behavior of oil sand.

Deformations as a Function of Oil Sand Composition

Oil sand composition is one fundamental phenomenon which influences its behavior (Jeremic, 1975). For example, it has been established that oil sand increases strength and decreases the percent of strain to failure with increase in the content of the solid phase. The laboratory test (uniaxial load at room temperature) shows that the plotted curves of strain versus time are separate for two compositions of bitumen – solid phase mixtures (Fig. 4).

It could be assumed that external stress and sample contraction will be carried in different ways as a function of the magnitude of the elastic and of the viscous components of the system (Van Der Poel, 1960).

If it is assumed that with a stress increase the spring is fully contracted and takes the whole load, the shear strenth of the system will depend on the magnitude of the elastic component. Thus the elastic component will break when the strength of the material is exceeded. From all the test data it is obvious that the magnitude of the elastic component (spring) is increased with decreasing bitumen content. The viscous deformation (dashpot) approached from the aspect of the bitumen content in the mixture suggests that shear

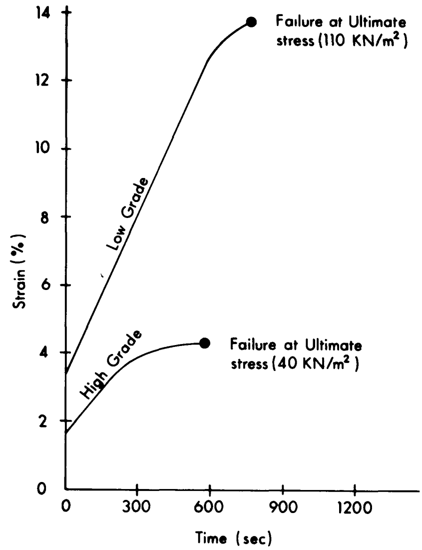

Fig. 4. Viscous flow of unconfined samples of various oil sand composition (at room temperature)

flow of the bitumen takes place some time before the sample failed, with mixtures of high bitumen content having a longer time of shearing motion than those of low bitumen content (Fig. 4). The viscous component will not show failure and so, an external stress can be carried to some extent by this component. Probably, the shearing displacement of the solid phase is governed by the flow of the dashpot, which separates sand grains along failure planes (Round, 1960).

However, the variation in flow for various compositions of oil sand is probably influenced not only by physical interaction between the solid and viscous phases, but also by some chemical interaction between the two of them (Carrigy, 1968). From visual observations of shear failures in the samples it could be concluded that interference of salid particles and their redistribution by bitumen during the loading process is a function of the percent of the solid phase (Jeremic, 1975).

Uniaxial Load-Time Deformations

Investigation of cylindrical remoulded oil sand samples has been conducted from two aspects: firstly, the deformation as a function of and instant constant load, and secondly, the deformation as a function of the removal of this constant load. The behavior of a bitumen-solid mixture for instant loading or unloading conditions with applied constant load as a function of time can be defined by rheological models (Van Der Poel, 1960; Ridgen, 1954). For example, the laboratory testing showed if the load was removed before failure set in, retarded elastic effects could occur and that part of the deformation becomes permanent: this suggests that a qualitative description of the bitumen-solid mixture might be offered by a Kelvin element in series with a Maxwell element. Since the total strain is the sum of these two elements, subsequently

$$\varepsilon=\varepsilon_1+\varepsilon_2$$

$$\varepsilon=\frac{\sigma_0}{E_1}+\frac{\sigma_0 t_1}{\eta_1}+\frac{\sigma_0}{E_2}\left(1-e^{-\frac{E_2 t_2}{2}}\right)$$

where

$\frac{\sigma_0}{E_1}$ is instantaneous elastic strain (instantly recoverable)

$\frac{\sigma_0 t_1}{\eta_1}$ irrecoverable strain resulting from the steady strain rate (viscous flow)

$\frac{\sigma_0}{E_2}\left(1-e^{-\frac{E_2 t_2}{2}}\right)$ exponential recoverable strain (retarded elasticity).

The time dependent phenomenon for volume deformation of oil sand can be assumed as follows:

– High grade oil sand shows an instant elastic effect at time zero, what is followed by retarded elasticity, and further deformation continues as a viscous effect.
– Simultaneous acting of all the elements of the model under loading and unloading conditions produces the volume-deformation effect of the oil sand.

The experiments on high grade oil sand samples showed that under repeated loading sometimes the retardation mechanism will have sufficient time to come into action and a failure stress below the original strength will be found. So actually at failure stress unloading and loading conditions, there is a clear tendency for the shear strength of the oil sand to deteriorate. This phenomenon has been noticed in the field during core sampling with increasing time from the recovery of the core (retardation mechanism), followed by volume of core deformation (Hardy and Hemstock, 1963), in agreement with our laboratory investigations (Jeremic, 1975).

Testing of the oil sand material in the field shows that its shear resistance decrease with depth (Hardy and Hemstock, 1963). This result suggests that retarded and viscous deformations have already developed in intact deposits due to geological cycles of loading and unloading during geological time, and that their values depend on the magnitude of the present load (i.e. weight of the overburden). From laboratory experiments it has been established that for a sample subjected to constant load, after unloading the shear strength of the sample deteriorated appreciably. In comparison, under very small load conditions (14 KN/m^2) retarded and viscous deformations are almost negligible and for this condition described model is not applicable.

Cyclic Load Deformations

Oil sand behavior during unconfined cyclic loading as a function of time has been investigated from two different aspects.

Cyclic loading without previously applied static load shows that the stress changes sinusoidally with time, and from the analysis of viscous damping can be written as the equation (Van Der Poel, 1960)

$$\sigma = \hat{\sigma} \sin \omega t$$

so that the oil sand should display a sinusoidal deformation with the same angular frequency:

$$\varepsilon = \hat{\varepsilon} \sin (\omega t - \Theta)$$

which is delayed by the phase angle Θ. This is similar to the static loading ratio between σ and ε which depends on the temperature, composition of mixture etc., as well as, the dynamic ratio between $\hat{\sigma}$ and $\hat{\varepsilon}$ which depends on the magnitude of the dynamic load, the number of cycles, temperature, composition of the mixture, and also on the frequency.

Laboratory investigations showed that cyclic loading supplied information not only for conditions of shear flow, but also for the phase shift Θ. This phase angle is a measure of the amount of shear energy dissipated in the material during one cycle, given by the equation

$$W = \int_0^{2\pi} \sigma \, d\varepsilon$$

which represents the work done in that time per unit of volume, and which is directly proportional to sin Θ. The mechanical angle of loss is Θ and this phenomenon itself is denoted as damping. For the oil sand energy can only be dissipated in the dashpot (viscous phase).

The main parameter is the magnitude of the stress during one cycle of load. For example, with an increase of magnitude of the cyclic load, the shear resistance of oil sand shows a deterioration: a sample of high grade oil sand at room temperature failed at 22 KN/m^2) cyclic load (Fig. 5). This phenomenon suggests that sinusoidal deformations of oil sand decrease its shear strength with an increasing load amplitude.

Dynamic load can cuase shear flow of the intact oil sand at the stress magnitude almost half that of a static load. If the oil sand is already loaded with overburden this phenomenon will be even grater, as shown in the next experiment.

Cyclic loading with previously applied static load simulated the oil sand deposit loaded by overburden under seismic effects. The test shows that for a small magnitude of cyclic loading, when the number of cycles is increased, the shear resistance of oil sand can be destroyed, probably due to structural viscosity. For example, a high grade sample was instantly loaded ($\sigma = 20$ KN/m^2). The

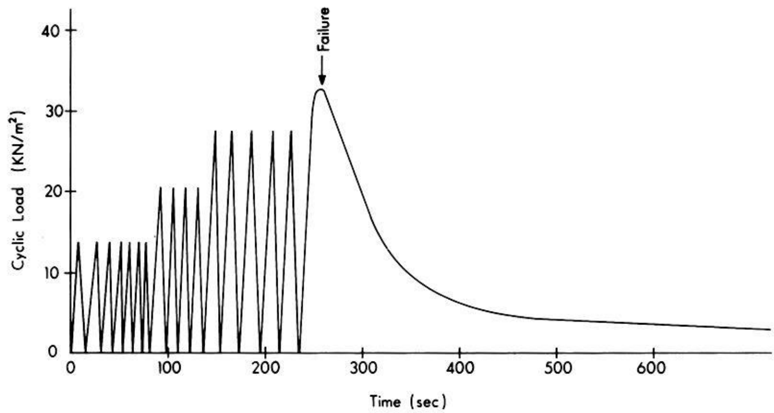

Fig. 5. Cyclic loading of high grade oil sand to failure at room temperature

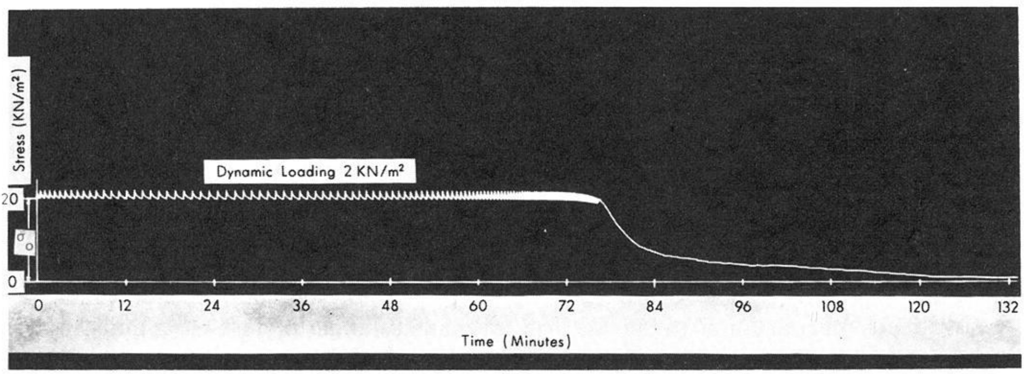

Fig. 6. High grade oil sand sample at instant stress cyclic loaded to failure at room temperature

experiment shows (Fig. 6) that with an increased number of cycles the retarded elastic recovery is also increased. The test carried on to failure shows a decrease of strain recovery before failure, probably due to shear flow already initiated. After failure occurs, the deformation curve as a function of time decreases almost parabolically and continues asymptotically to the times axis.

Hydrostatic Pressure Deformations

The laboratory investigations of oil sand under confined pressure in the triaxial cell showed that applied vertical pressure (higher magnitude) and lateral pressure (lower magnitude) tend to be redistributed. The redistribution of applied stress is toward their equalization, and they became equal at approximately 3.5 MN/m^2. This phenomenon suggests that oil sand deposits exposed to overburden

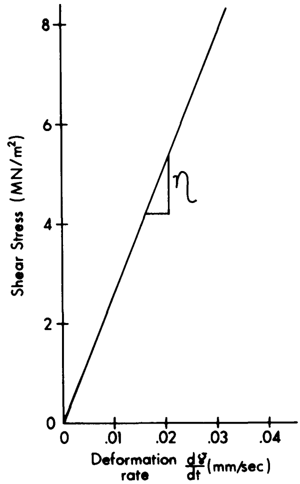

Fig. 7. Stress/deformation relations for hydrostatic pressure (high grade oil sand sample, at room temperature)

pressure at some depth might be in a state of hydrostatic pressure. Oil sand behavior under hydrostatic stress conditions has been investigated from two aspects.

Oil sand deformation under hydrostatic pressure (vertical and lateral pressures are equal) has been observed under laboratory conditions on cylindrical oil sand samples placed in a triaxial cell (Soiltest), loaded vertically by Instron frame and horizontally by improvised apparatus for lateral pressure. In figure 7 is illustrated a typical diagram of oil sand deformation under hydrostatic pressure. It is noticeable that for applied hydrostatic pressure, there are linear relations between stress and rate of deformation. This phenomenon suggests that at hydrostatic stress the shear strength of the oil sand is overcome and behaves like a Newtonian viscous substance (dashpot). This behavior can be represented by a rheological equation in which the shear stress is linearly related to the rate of shear strain, that is

$$\tau = \eta \frac{d\gamma}{dt}$$

where η represents the coefficient of proportionality and is determined by the viscosity of the pure bitumen. This equation clearly states that the intensity of deformation is a function of the magnitude of the coefficient of viscosity of the bitumen phase.

Accepting the possibility that the oil sand under hydrostatic pressure behaves like a Newtonian model, its deformation might be considered from the aspect of flow deformation. Oil sand properities as a four-phase system should be effected by behavior of each phase under hydrostatic pressure. It is obvious that solid phase (sand particles) and viscous phase (bitumen) will behave differently, under hydrostatic pressure due to their differing physical properties. These differences will effect the structural deformation of the system.

Structural deformation under confined pressure is mainly effected by the viscous flow of bitumen within the oil sand mixture. The flow of bitumen caused a noticeable change in the internal structure of the oil sand. For example a remoulded high grade oil sand sample with uniform bitumen distribution, after subjection to higher confinement has a bitumen content redistributed in a particular pattern. This pattern suggests that during loading pressure, the bitumen layers had been forced upwards and inwards by shearing stress. This is shown by the increase in bitumen concentration on the top of the sample and the sand concentration on the bottom and around the walls of the cylinder (Fig. 8). The sand particles were probably rearranged during bitumen flow, so as to make flow easier.

This phenomenon suggests that oil sand under higher confinement deforms by bitumen flow, which is mostly upward. Although structure deformation does not influence the mechnism of flow, it does follow the linear function of a Newtonian viscous body. It could be assumed that oil sand under sufficiently high pressure (zero shear strength) acts like an incompressible fluid without initial shear resistance. If this assumption is acceptable a hydrodynamic theory might be applied to analyse further the behavior of oil sand at higher confining pressures.

Conclusions

The behavior of oil sand is a very complex problem which should be investigated in the field in two ways: first, the behavior of oil sand in intact deposits as functions of the overburden pressure, composition of the mixture, and geothermal gradient; second, the behavior of oil sand within a mine structure as functions of the loading and unloading mechanism of deformation, increase of temperature, and also the size of the mine opening.

The laboratory investigations suggest that the main part of the intact oil sand deposits might behave like a Newtonian viscous body due to load (overburden pressure) and time (geological time). With the assumption of deformation sufficiently high that oil sand acts like a fluid without initial shear resistance, conventional subsurface mining systems cannot be applicable. For this possible behavior of oil sand, some unconventional exploitation method should be utilized to obtain a huge mass flow of caved oil sand.

Volume deformation, with a volume extension toward an opening, might be a phenomenon which will seal the opening and stop further caving and oil sand flow. Any shear strength in the material will deteriorate, but movement of the material will not be initiated.

At present many geophysical laboratories throughout the world conduct very sophisticated research involving explosion and their related seismic effects in thin layers, including hydraulic fracturing of rocks, temperature increases and heat flows in rock layers, and seismicity of rock layers under high pressure. Some of these research results might be applied to investigations of inducing flow of oil sand and accelerating its flow during mining. Thus geophysical applications may go beyond exploring for oil sand into methods of extracting oil sand.

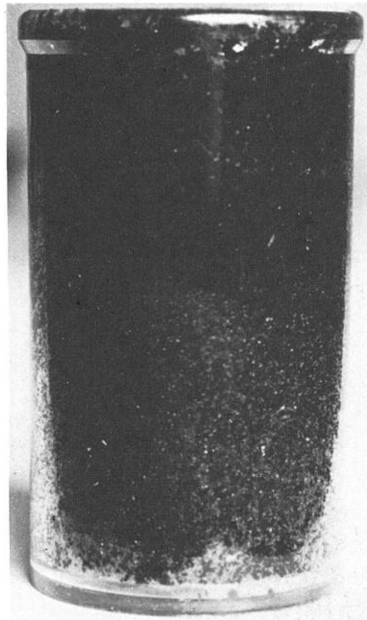

Fig. 8. Bitumen flow under higher confined pressure (7 MN/m^2) at room temperature

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