Sustainable Use of Oil Sands for Geotechnical Construction and Road Building

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ABSTRACT: Oil sands are natural deposits of bituminous sand materials that are mined and processed for crude oil. They are routinely used in oil sand fields for building temporary and sometimes permanent roads serving mining and hauling activities. Although the principal application of these materials for road building has been in the unbound layers of the pavement structure, the full benefits of oil sands, particularly, their sustainability and environmental friendliness are yet to be realized. In their natural state, oil sands have similarities to cold mix asphalt mixtures which are often comprised of uniformly graded fine to medium sands and used for pavement repair and patching applications. Yet, they may exhibit complex stress dependent characteristics and viscoelastic and plastic behavior under dynamic loading of mining and off-road construction equipment. This paper presents findings from a comprehensive laboratory research program conducted on three types of oil sand materials with the main goal to characterize their engineering behavior. The research efforts focused on establishing a suite of tests to determine strength, modulus and deformation characteristics under realistic traffic loading and climatic conditions. The developed suite of tests established essential trends in oil sand behavior for developing laboratory guidelines and test protocols and typical material characterization models for their sustainable use in geotechnical and road building applications.

KEYWORDS: Oil sands, bituminous materials, modulus, shear strength, permanent deformation, pavements, sustainable construction

Introduction

Oil sands, also referred to as tar sands, is a generic name given to natural deposits of bituminous sand materials that are rich in bitumen content to the extent that oil can be extracted from these deposits. These materials are mainly found in Canada, United States and Venezuela. The largest deposits are located in the Alberta province in Canada. In 2004, about 170 million tons of oil sands were mined in Canada. The typical high content of bitumen in the oil sand composition makes these naturally occurring sands low load-bearing materials for haul trucks, shovels and other construction and mining equipment. In situ, the oil sand deposits are predominantly quartz sand surrounded by a thin film of water and fines, with bitumen filling the pore spaces between the sand grains. The quartz sand, silt, and clay, i.e., the inorganic materials of the oil sand composition, normally constitutes about 80 % by weight with bitumen and water constituting about 15 % and 5 %, respectively [1].

Low grade oil sands, i.e., bitumen content less than about 9 % by weight, are used as unbound construction materials for temporary and permanent roads in oil sand fields for operating haul trucks and shovels. High grade oil sand materials contain in excess of 16 % bitumen. The use of oil sand materials has been limited to access roads in the mining pits with little or no environmental concerns. Oil sands would be environmentally friendlier and consume substantially less energy than hot mix asphalt structural layers built routinely as flexible pavement surface courses. To date, no study has directly focused on the potential use of oil sands in road building. Further, despite using excessive quantities of the tailings for landfills, the oil sand materials can be reclaimed and converted for geotechnical construction and applications. This would help mitigate potential depletion of high quality mineral aggregate sources and provide means to deal with various oil sand environmental issues i.e., green gas emissions and disposal of sand residue (tailings) during mining and processing/extraction of the bitumen from the sand.

Oil sand materials often experience varying magnitudes of static and dynamic loads applied in vertical and horizontal directions during mining operations of heavy off-road haul trucks and shovels in the mining pit [2]. These materials often exhibit complex stress dependent characteristics and viscoelastic and plastic behavior under this large capacity construction and mining equipment. Field studies have shown that the modulus and deformation behavior of oil sands are primarily dependent upon the applied load magnitude, temperature, amount of bitumen, and the rate of loading or frequency [2]. However, early experimental research studies on oil sands have primarily focused on using static loading conditions to obtain stress-strain data to characterize their shear strength and only the elastic properties of these materials [3-8]. Based on the data collected in these studies, confining pressure, peak stress or strain, friction angle and cohesion were among the material properties used for modeling the strength and elastic modulus and deformation behavior. To properly characterize behavior of these bituminous sand materials, laboratory tests should closely simulate field densities and loading conditions and adequately address the actual time and temperature dependent plastic deformation accumulation under static, dynamic, repeatedly applied wheel loading conditions.

The objective of this paper is to present findings from a comprehensive laboratory research study that focused on establishing a suite of tests to characterize both static and dynamic properties of oil sand materials under typical field loading conditions of construction and mining off-road haul trucks and shovels. In addition, performance characterization models to account for rutting and other pavement distresses experienced by off-road haul trucks and shovels during oil sand field activities are presented. Details of the study and the database established through the oil sand test procedures are presented elsewhere [9-14].

Oil Sand Materials Tested

Physical Properties

The three types of oil sand materials studied were obtained from Suncor Energy, Inc. and Syncrude Canada Ltd. oil sand mines in Canada. The selection of these samples was mainly based on their field loading behavior under construction and mining equipment, and the on-going research on these materials. Suncor Energy, Inc. provided two oil sand materials (SE samples) whereas Syncrude Canada Ltd. provided one oil sand material (AU sample). The oil sand samples were shipped in separate barrels from Caterpillar, Inc. Technical Services Division in Peoria, Illinois to the University of Illinois Advanced Transportation Research and Engineering Laboratory (ATREL) for these studies.

The oil sand samples were initially tested for bitumen and water contents using American Association for State Highway and Transportation Officials (AASHTO) test procedures AASHTO T 308 and T 265, respectively [15, 16]. Following the AASHTO T 308 [15] test procedure, about 1500 g of each oil sand sample was placed in the ignition oven, which was preheated at the temperature of 482^{o}C to determine the bitumen contents. The ignition test was conducted on three repeated specimens of each oil sand sample. The bitumen contents were obtained after ignition, i.e., when constant weight of the sample was achieved. An average maximum temperature achieved for ignition was about 526^{o}C, 552^{o}C, and 569^{o}C for SE-09, SE-14 and AU-14, respectively. The water contents were all obtained at the temperature of 110^{o}C using the AASHTO T 265 [16] test procedure. The bitumen contents were found to be 8.5 %, 13.3 % and 14.5 % for the SE low grade, SE high grade and AU high grade, respectively; and the water contents were 1.4 %, 3.2 % and 2.2 %, respectively. The SE samples were designated as SE-09 and SE-14, and the AU was designated as AU-14 according to their respective bitumen contents.

After separating bitumen from the oil sands through burning in the oven, washed sieve analysis tests were conducted on the sand ingredients to determine particle size distributions of the three oil sands using AASHTO T 27 [17]. All the three oil sand samples were uniformly graded fine to medium sands with the smallest to largest size particles ranging from 0.6 mm to 2.36 mm and the fines contents, i.e., passing No. 200 sieve or 0.075 mm, ranging from 7 % to 15 %. The gradation results of the three oil sand samples were similar to grain size distributions for typical oil sand materials reported by Cameron and Lord [18]. Table 1 shows the detailed results of the physical property tests conducted on the three oil sand samples.

TABLE 1—*Physical properties of the three oil sand samples.*

Oil Sand ID	w [%]	w_b [%]	D_{10}	D_{30}	D_{50}	D_{60}	C_u	C_c
SE-09	1.4	8.5	0.07	0.12	0.17	0.19	2.9	1.17
SE-14	3.2	13.3	0.08	0.14	0.18	0.21	2.8	1.24
AU-14	2.2	14.5	0.09	0.17	0.22	0.27	3.0	1.19

w = water content;
w_b = bitumen content;
D*i* = grain size (mm) corresponding to *i-percent* passing by mass;
C_u = coefficient of uniformity;
C_c = coefficient of curvature.

Sample Preparation

The oil sand samples were prepared for the laboratory testing program using an Industrial Process Controls (IPC), Australia, servopac gyratory compactor. The samples were compacted at different density levels depending on the applied number of gyrations at the approximate density states in the field using the gyratory compactor. Typical compaction specimens of 150 mm diameter by 150 mm high were produced for each oil sand sample at room temperature of approximately 21^{o}C. The typical bulk densities achieved in gyratory compaction for SE-09 and SE-14 were 2,000 kg/m^3 at 100 gyrations and 2,050 kg/m^3 at 40 gyrations, respectively. The density achieved for AU-14 was 2,050 kg/m^3 at 25 gyrations. These achieved densities obtained for the cylindrical specimens were very close to field density values reported by Joseph [2]. Following compaction, specimens were conditioned at the desired temperatures for a minimum of six hours in a temperature chamber for testing. Figure 1 shows loose and compacted AU-14 and SE-09 samples and the IPC gyratory compactor used to prepare specimens for all the three oil sand samples for testing.

FIG. 1—*Oil sand loose samples, samples prepared, and compaction equipment.*

Recent research studies have investigated and established a close agreement between the modulus results obtained from samples at diameter to height ratios of 1:1 and 1:2 [19, 20]. Especially, when determining resilient modulus from the vertical specimen response, i.e., standard definition, changing the specimen height did not make a difference in the modulus values computed [19, 20]. Moreover, a negligible end friction could still be attained in a triaxial set up with a 1:1 sample size ratio by placing a smooth plastic coated paper between the polished platen and specimen [21], which proved to minimize specimen end effects in modulus testing.

Suite of Laboratory Test Procedures

One of the main objectives of this study was to develop new laboratory test procedures to properly characterize field loading behavior of oil sand materials. The test procedures were intended to provide strength, modulus, and deformation properties needed for developing material behavior models for oil sand materials under field loading conditions of typical haul trucks and other construction, and mining equipment. For the various viscous, elastic and plastic material models to be developed, five different test procedures were developed for determining material properties for oil sand materials. The developed test procedures mainly are based on field loading conditions of construction and mining haul trucks and shovels. The test procedures include; hydrostatic loading, monotonic loading shear strength, repeated load triaxial, pure shear loading, and dynamic modulus tests.

Experimental Design Parameters

The loading characteristics of off-road large capacity construction and mining equipment dictate field loading stress states, and therefore, directly influence the deformation and stiffness behavior of oil sands in the field. For instance, Joseph [2] noted from field studies that a Caterpillar 797B off-road haul truck could produce vertical stresses of about 800 kPa with confining stresses ranging between 250 and 300 kPa. He also observed that the P&H 4100 type BOSS shovels generated a static ground loading of up to 220 kPa, and could induce a ground confinement of about 70 kPa [2]. The confinement under trucks could be up to approximately 300 kPa. Joseph [8] reports that oil sands experience extreme temperatures of +40^{o}C in summer and -40^{o}C in winter to make them more problematic to construction and mining equipment during summer or warmer months than in winter. Oil sand materials soften and become problematic at temperatures above 28^{o}C in the field during warmer months to the extent that triaxial test could not be performed on oil sand materials with bitumen contents higher than 14 % [2]. Under colder seasonal conditions there is little concern about oil sand materials since they become stiff enough to support field equipment operations [8].

The experimental program carried out on the three oil sand samples focused on conducting strength, deformation and modulus tests under simulated close-to-field densities and applied stress states at different load pulse durations (or loading frequencies) and temperatures. A comprehensive laboratory test program was developed in order to obtain large amount of test data for the oil sand modeling. The laboratory testing program was conducted at two temperatures, 20^{o}C and 30^{o}C to account for spring and hotter summer periods in the oil sand fields in Canada, respectively. Further, loading frequencies that range between 2 and 10 Hz and load pulse durations of 0.1-and 0.5-seconds were also included in the laboratory testing program to consider the effects of different trafficking speeds of haul trucks and shovels of other mining equipment in the field.

Testing Equipment

The test procedures needed to utilize testing equipment and devices capable of simulating in the laboratory, wide range of stress conditions, i.e., low to high stresses, static and dynamic stresses experienced by the oil sand materials in the field. An IPC servo-pneumatic testing device, Universal Testing Machine (UTM) was deemed suitable for the developed test procedures. The IPC UTM is a closed-loop servo control loading system. The main part of the system consists of loading frame, triaxial cell, control and data acquisition system, integrated software package and personal computer. The nature of the frame limits deflection and vibrations which could influence the accuracy of measurements especially when both axial and radial dynamic repeated loadings are applied on the sample at the same time.

Two main UTM triaxial testing devices at ATREL, the University of Illinois FastCell (UI-FastCell), and IPC rapid triaxial testing cell (RaTT cell) were conveniently used for the oil sand materials testing. The two test setups were extensively used to characterize the modulus behavior of bituminous and granular materials [20, 21]. The selection of the advanced triaxial testing equipment was based on their unique capabilities. In addition to pulsing stresses in the vertical direction, these testing devices offer the extra capability to apply dynamic stresses in the radial/horizontal direction to better simulate field stress states under traffic/moving wheel loads and measure anisotropic material stiffness properties if needed. Both the UI-FastCell and RaTT cell use a one to one (1:1) height to diameter ratio for their test specimen with no need for specimen trimming and gluing to end plates.

The IPC UTM setup and the RaTT cell are commercially available. However, it is worth mentioning that the test procedures developed in this study were not limited to a particular type of testing device. The precise choice of the testing equipment and conditions depend on the capabilities of the device and flexibility of the software associated with the testing system. Figures 2 and 3 show the UI-FastCell and RaTT cell test setups used for asphalt and granular materials testing at ATREL, respectively. While the RaTT cell is a pneumatic device for the vertical and radial specimen loading, the UI-FastCell uses an air over fluid interface and is capable of uniquely applying static and dynamic load combinations in excess of 500 kPa through the pressurized fluid in the horizontal chamber.

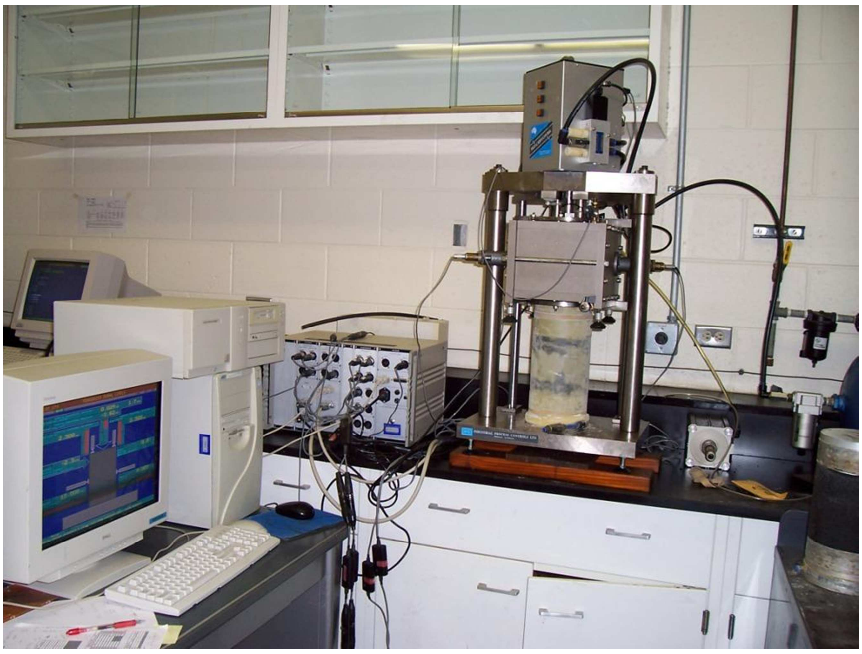

FIG. 2—*UI-FastCell advanced triaxial test setup at ATREL.*

FIG. 3—*RaTT Cell advanced triaxial test setup at ATREL.*

Oil Sand Test Procedures

Hydrostatic loading test procedure

The hydrostatic compression loading test procedure developed was intended to generate test data to determine bulk modulus and volumetric strain properties of the oil sand materials. Bulk modulus relates directly to the volume change of the material, and it can be used to model the volumetric deformation due to hydrostatic loadings. The hydrostatic compression test was conducted on the 150 mm diameter by 150 mm high gyratory compacted oil sand samples. During testing, gyratory compacted oil sand specimens were subjected to a sequence of different applied hydrostatic (isotropic) compression stresses of 41.4, 69, 138, and 276 kPa. Specimens were loaded from zero stress condition to an individual hydrostatic stress, unloaded to zero, and then, reloaded to the next stress state until the maximum hydrostatic stress of 276 kPa was reached (i.e., 0 → 41.4 kPa → 0 → 69 kPa → 0 →138 kPa → 0→ 276 kPa → 0). A pulsed wave shape with 60-second loading and 60-second unloading was applied on the test specimens.

The axial static loading was controlled by the vertical load cell, and the radial loading was measured by a pressure transducer. Both axial and radial deformations were measured by two symmetrical linear variable displacement transducers (LVDTs) for each load cycle and the corresponding axial and radial strains (ε_1 and ε_3) were computed for the test specimens. Replicate tests were performed for each type of oil sand material, i.e., SE-09, SE-14, and AU-14, to establish the full laboratory test matrix. Overall, 12 tests were conducted on the three oil sand samples at two temperatures, 20^{o}C and 30^{o}C.

The bulk moduli K of the oil sand samples were calculated from the ratio of the incremental hydrostatic stress $\Delta\sigma$ to the incremental volumetric strain $\Delta\varepsilon_v$. Eq. 1 was used to define the bulk modulus of the oil sand samples:

$$K = \frac{\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3}{\Delta\varepsilon_v} = \frac{\Delta\sigma}{\Delta\varepsilon_v} \qquad (1)$$

where the volumetric strain ε_v is computed from the axial strain ε_1 and the radial strain ε_3 as $\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$, and for triaxial compression tests, hydrostatic stress is given by $\sigma = \sigma_1 = \sigma_2 = \sigma_3$.

Shear Strength Test Procedure

A monotonic loading shear strength test was developed to provide shear strength properties of the oil sand materials. Shear strength properties of geomaterials are important inputs to finite element models that incorporate Mohr-Coulomb failure criteria. The results from such tests would provide failure criteria to be employed in analyzing the stability of the tested materials.

Triaxial compression monotonic test was initially proposed for the oil sand materials. The triaxial tests were performed on cylindrical specimens, 71 mm in diameter and 142 mm high, by applying five confining stress levels, i.e., 20.7, 41.4, 69, 138 and 276 kPa. Specimens were conditioned and tested at temperatures of 20^oC and 30^oC to obtain the friction angle ϕ, and cohesion c properties. The test specimens were monotonically loaded at a strain rate of 1 % strain/minute using an IPC UTM-5P pneumatic testing system, and pressurized in a triaxial chamber using air. The triaxial test results indicated that the oil sand samples were found to give essentially similar shear strength properties regardless of the applied confining pressure. Apparently, the oil sand materials did not densify as confining pressure increased, hence the shear strength did not increase, i.e., there was no or negligible interlock between the sand grains of the materials and the oil sands were primarily cohesive in nature. The zero friction angles obviously were not characteristic of the dense nature of the tested oil sand materials. Dusseault and Morgenstern [3] and Agar et al. [22] report that oil sands derive its strength from the dense interlocking grain structure it exhibits. Thus, there would be significant contact between the grains of the oil sands tested to produce friction angle.

In a related case, Dusseault and Morgenstern [3] abandoned triaxial tests in favor of direct shear testing for Athabasca oil sands. One of the reasons was that sample uniformity and the required number of similar specimens to describe Mohr-Coulomb envelopes could not be obtained from triaxial testing. Similarly, in this study, direct shear tests were selected for the oil sand materials instead of triaxial shear tests. The results from the direct shear tests were comparable to properties of oil sands reported earlier from previous laboratory studies [3, 22-24].

Prismatic specimens were used to conduct the direct shear tests on the three oil sand samples. The shear specimens were produced from the gyratory compacted 150 mm diameter by 150 mm high cylindrical specimens. Using a masonry saw, the gyratory compacted specimens were cut into square prismatic specimens, 100 mm size and approximately 30 mm high, for direct shear testing. The direct shear tests were performed by applying six normal stress levels, i.e., 20.7, 41.4, 69, 138, 276 and 552 kPa at test temperatures of 20^{o}C and 30^{o}C to obtain the friction angle ϕ, and cohesion c properties. The direct shear tests were performed using a Humboldt pneumatic direct shear test setup at ATREL. The shear stress was measured through the load cell and the horizontal and vertical deformations were measured using horizontal and vertical LVDTs.

The shear strength properties were obtained from a continuous record of shear strain and shear stress attained at or until sample failure. The linear Mohr-Coulomb envelopes were used to model the shear strength properties of the oil sand samples (see Eq. 2).

$$\tau_{\max} = c + \sigma_{\mathrm{n}} \tan\phi \tag{2}$$

where, $\tau_{\max}$ = shear strength; σ_{n} = normal stress at failure; c = cohesion intercept, $\tan\phi$ = slope of the failure envelope (ϕ is friction angle).

Repeated Load Triaxial Test Procedure

Repeated load triaxial tests are commonly used to determine the modulus and deformation properties of pavement materials [25]. The test results are mainly used to characterize the stress dependent resilient modulus behavior of the materials tested. The deformation trends of the oil sand materials under off-road haul trucks, shovels and other construction and mining equipment loading can be conveniently characterized by plastic (permanent) and elastic (resilient) strains. The material's permanent deformation characteristics are important for developing characterization models to predict sinkage or field rutting potential, and the resilient properties may be used to characterize the stiffness behavior of the constructed oil sand layers.

The repeated load test procedure developed for the oil sands was used to collect both resilient modulus and permanent deformation characteristics. Although a much higher number of load applications would preferably be applied to accumulate permanent deformations in the specimen, conducting these tests separately would be very time-consuming and costly. Note that permanent deformation test is basically destructive, and only one (deviator stress to confining pressure) stress ratio can be applied to one specimen at a time. As a result, this study employed the same load pulse durations to evaluate both the modulus and permanent deformation properties. Also, testing a new specimen for each stress ratio eliminated any stress history effects on the permanent deformation results.

The repeated load triaxial test was conducted on the 150 mm diameter by 150 mm high gyratory compacted oil sand samples. During testing, gyratory compacted oil sand specimens were subjected to three different constant confining pressure levels (i.e., σ_3 = 41.4, 138 and 276 kPa) and three deviator stress levels (i.e., σ_d = 41.4, 138 and 276 kPa) to constitute a total of nine different applied stress states. Each deviator stress σ_d (= $\sigma_1 - \sigma_3$) and constant confining stress σ_3 pair was applied on one specimen with the deviator stress repeatedly pulsed in the vertical direction for a total of 1,000 load cycles except for the replicate tests, which were performed at σ_d = 138 kPa and σ_3 = 138 kPa only for a total of 10,000 load cycles and later used to check permanent deformation model performances. The resilient modulus (M_R) test data were collected at the end of 100 load cycles.

A total of 36 tests were designed for each type of bituminous sand material, i.e., SE-09, SE-14, and AU-14, to establish a full factorial test matrix. That is, nine applied stress states with the σ_1 to σ_3 stresses were repeated at two temperatures, 20°C and 30°C, and two haversine load pulse durations of 0.1- and 0.5-seconds with 0.9- and 0.5-seconds rest periods, respectively. The specimen's vertical displacement was determined by averaging readings of the two axial LVDTs.

Permanent deformations (δ_p) were recorded for each load cycle and the corresponding plastic strains (ε_p) and elastic/resilient strains (ε_r) were computed at these different number of load applications. The stress states applied were recorded, and the resulting recoverable axial strain responses of the specimen are measured. The average recoverable axial strain ε_r and the applied deviator stress σ_d of the last five cycles were used to compute the resilient modulus M_R of the oil sand materials (see Eq. 3).

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{3}$$

Pure Shear Loading Test Procedure

The pure shear test was performed for obtaining the shear modulus of the oil sand materials as a function of the applied stress states. Currently, the conventional ASTM cyclic triaxial test is the commonly used procedure for measuring shear modulus properties of soils in the laboratory [26]. In this test, the confining stress is typically held constant while the deviator stress is applied cyclically on the sample. The shear modulus is evaluated from modulus of elasticity by assuming a representative Poisson's ratio for the material tested. The most realistic shear loading, however, occurs when cyclic confining and dynamic stresses are applied simultaneously on the sample. Obtaining such a loading condition in the laboratory would enable close simulation of the roll and bounce and rocking motions of haul trucks and shovels on oil sand materials in the mining pits. No laboratory test procedure or set of data is currently available to determine shear modulus properties of oil sand materials.

The developed pure shear test procedure for the oil sand materials provides static and dynamic data in both axial and radial directions to evaluate shear modulus of oil sand materials. The shear modulus values obtained from the developed test procedure can be used to characterize the shear stress induced in the materials by the mining haul trucks and shovels. The test was performed on the 150 mm diameter by 150 mm high gyratory compacted oil sand samples. For the application of the pure shear stresses, two alternating pulses of the same magnitude were applied at the same time in the vertical and radial directions on the oil sand samples.

Figures 4*a* and 4*b* show the 90 degree out of phase cyclic stresses, $\Delta\sigma/2$ (or $\sigma_d/2 = \tau_{cyc}$), by which the vertical stress is increased (or decreased). The radial stress is also increased (or decreased) at the same time by $\Delta\sigma/2$. The applied stress path is in the vertical direction similar to that of pure shear loading that would be induced in the field by large capacity off-road construction and mining equipment on the oil sand materials. The pure shear loading is indicated in Fig. 4*c* by the vertically oriented stress path, $\pm\tau_{cyc}$, on a shear stress q (= $\sigma_1 - \sigma_3$) - effective mean pressure p [= $(\sigma_1+2\sigma_3)/3$] plot.

Overall, the pure shear tests were conducted on 18 oil sand specimens at three radial (confining) stress levels of 41.4, 69, 138 kPa, and shear stress levels of 20.7, 41.4, 69 and 138 kPa. For each confining stress, a minimum dynamic/cyclic shear stress of 20.7 kPa was applied on the test specimens, and increased until the shear stress reached a value equal to the maximum confining stress (i.e., 138 kPa). A full factorial test matrix comprising 54 tests included two test temperatures, 20°C and 30°C, and loading frequencies of 2 and 10 Hz.

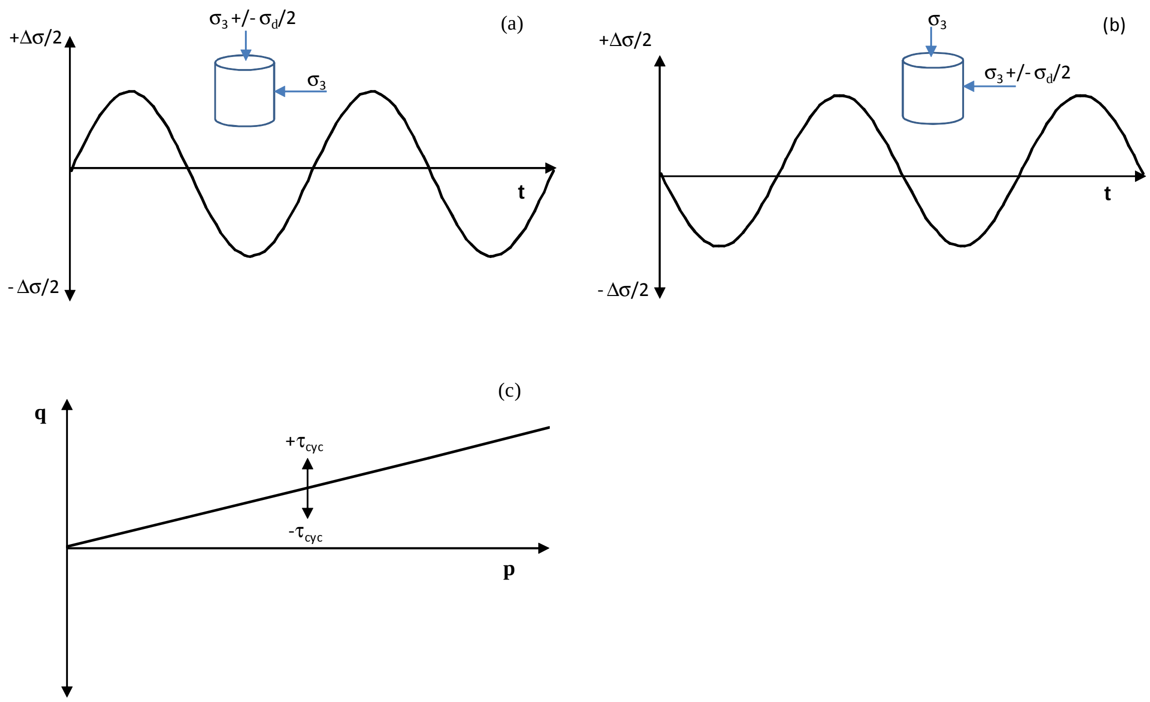

FIG. 4—*Pure shear loading applied on the oil sand specimen.*

At different stress levels strains were recorded in vertical and radial directions. The shear modulus (*G*) is calculated using the measured shear strain and the applied shear stress (Eq. 4).

$$\tau = \sigma_1 - \sigma_3; \quad \gamma = \frac{2}{3} \times (\varepsilon_1 - \varepsilon_3); \; G = \frac{\tau}{\gamma} \tag{4}$$

where, τ = applied shear stress, σ_1, σ_3 = axial and radial (confining) stresses, respectively, γ= shear strain, ε_1 and ε_3 are axial and radial strains, respectively.

Dynamic Modulus Test Procedure

Dynamic modulus test provides data to calculate dynamic modulus and phase angle of bituminous materials. The values of dynamic modulus and phase angle are used as performance criteria for bituminous materials over a range of loading frequencies and temperatures. The dynamic modulus test procedure developed for oil sand materials applied stress states to adequately determine dynamic modulus properties and characterize the stiffness behavior of the oil sand materials.

The dynamic modulus test was conducted on the 150 mm diameter by 150 mm high gyratory compacted oil sand samples. During testing, gyratory compacted oil sand specimens were subjected to a cyclic stress of 41.4 kPa and constant confining stress levels of 41.4, 69, 138 and 207 kPa. A sinusoidal load waveform with no rest period was applied at loading frequencies of 2, 5 and 10 Hz, and two test temperatures of 20°C and 30°C. At different constant confining pressures, cyclic/dynamic stress was applied on the specimen, and stresses and strains in vertical direction were recorded to compute dynamic modulus properties of the materials tested. The specimen's vertical deformation was determined by averaging readings of the two axial LVDTs. Axial stresses and the corresponding axial strains were recorded for five load cycles for each test to compute the dynamic modulus properties of the oil sand materials. In this study, a total of 24 tests were designed for each oil sand material to establish a full factorial test matrix. That is, the cyclic stress was applied on each oil sand sample at the four different confining stress levels, two test temperatures of 20°C and 30°C and three loading frequencies of 2, 5, and 10 Hz.

For viscoelastic materials such as these oil sands, the stress-strain relationship under a continuous sinusoidal loading is defined by a complex number called the complex modulus E* [27, 28]. The complex modulus has real and imaginary parts that define the elastic and viscous behavior of linear viscoelastic materials. The absolute value of the complex modulus is defined as the material's dynamic modulus. For the one-dimensional case of a sinusoidal loading, the applied stress and the corresponding strain can be expressed in a complex form given by Eqs. 5*a* and 5*b*, respectively.

$$\sigma^* = \sigma_0 e^{i\omega t} \quad (5a)$$

$$\varepsilon^* = \varepsilon_0 e^{i(\omega t - \delta)} \quad (5b)$$

where σ is the applied stress, σ_0 is the stress amplitude; ε is the strain response, ε_0 is the strain amplitude; ω is angular velocity, which is related to frequency by $\omega = 2\pi f$; $f = 1/T$; t is time, and T is period; δ is the phase angle related to the time the strain lags behind the stress. Phase angle is an indicator of the viscous (or elastic) properties of the viscoelastic material. For a pure elastic material, $\delta = 0°$, and for a pure viscous material, $\delta = 90°$. Mathematically, the dynamic modulus is defined as the maximum (peak) dynamic stress divided by the recoverable maximum (peak) axial strain. From Eqs. 5*a* and 5*b*, the complex modulus, $E^*(i\omega)$, is defined as the complex quantity in Eq. 6.

$$E^*(i\omega) = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0} e^{i\delta} = E' + iE'' \quad (6)$$

The real part of the complex modulus is the storage modulus (E') and the imaginary part is the loss modulus (E''). The dynamic modulus $|E^*|$ is the absolute value of the complex modulus, which is defined mathematically in Eq. 7.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (7)$$

At different stress levels strains in vertical and radial directions wre recorded to compute dynamic modulus of the material. Dynamic modulus $|E^*|$ and phase angle δ were computed from the test data.

Models Developed for Oil Sands

Characterization Models

A large amount of database established from the laboratory testing program for the entire five test procedures were used to develop various material characterization models for the oil sand samples tested. Details of the test data and results of individual test procedures are presented for each oil sand material tested, i.e., SE-09, SE-14 and AU-14 samples, elsewhere [9-14]. For example, the complete test data for the dynamic modulus test procedure generated about 6,000 data points for one oil sand sample from 12 stress states at two test temperatures. Thus, a single data set for one oil sand sample at one temperature comprises of 250 stress-strain data points. The high number of data points obtained through the laboratory test factorial for each test procedure statistically provided high confidence in the characterizations models developed.

Since the overall objective was to develop a better basic understanding as well as to establish practical predictive equations to estimate sustainable engineering field performances of oil sands, the stress-strain data sets obtained from the laboratory testing program were combined to create individual databases of the three oil sand materials. A close examination of the physical properties of the three oil sands; particle size distribution, density, and water content suggested that the individual databases could also be combined for analysis. Previous research also indicated that oil sand materials generally, have similar physical properties [2, 3, 18]. Therefore, it was reasonable to combine the test data to develop a generalized set of characterization models applicable to oil sands. The combined database allowed bitumen content to be included as a variable in the analyses with the assumption that bitumen rheological properties were similar among all the three oil sands.

The correlation coefficient (R-square) selection method in the SAS software was first used to determine which variables were potential candidates for the models. The variables used in the SAS stepwise selection method include the applied stress states (principal stress ratio σ_1/σ_3, deviator stress σ_d, hydrostatic stress σ, confining pressure σ_3, bulk stress θ), number of load applications N, temperature T, loading frequency f, bitumen content w_b, water content w, gradation properties (C_u, C_c and D_i) as independent variables, and moduli (bulk modulus, shear modulus, resilient modulus, and dynamic modulus), and permanent strain as dependent variables. The statistical analyses results showed that the oil sands moduli and permanent strain were to a large extent independent of the gradation properties, water content. There was virtually no correlation between all the three gradation properties and moduli, as well as permanent strain ($R^2 < 0.2$). It was found that the modulus of the oil sand materials and permanent strain strongly depended on the applied stress states, temperature, bitumen content, and the number of load applications. Oil sands are bituminous materials, whose characteristics would be greatly influenced by temperature, and loading frequency. For viscoelastic materials, the influence of increasing loading frequency is generally similar to the effect of decreasing temperature on stiffness or deformation. It is well documented that temperature directly affects modulus and deformation properties of bituminous materials. This suggests that having a temperature in the model may provide a better indication than including loading frequency in the model. Therefore, temperature was used as independent variable instead of the loading frequency in the models.

The correlation coefficient (R-square) selection method in the SAS software was first used to determine which independent variables were potential candidates for the models. The variables used in the selection include principal stress ratio σ_1/σ_3, deviator stress σ_d, hydrostatic stress σ, confining pressure σ_3, bulk stress θ, number of load applications N, bitumen content w_b, water content w, temperature T, and the gradation properties (C_u, C_c and D_i). It was found that the modulus of the oil sand materials and permanent strain strongly depended on the applied stress states, temperature, bitumen content, and the number of load applications.

Various mathematical forms such as linear, nonlinear, logarithmic, and hyperbolic were investigated using multiple regression analyses. Considering the typical exponential growth of modulus and permanent strains in the triaxial tests, the power function was found to be the most suitable for the models. Based on this result, several models were selected to study the behavior trends of the oil sand materials. The SAS statistical software was used to perform multiple regression analyses on the data sets to obtain the model parameters [29].

Generalized Models for Oil Sands

Table 2 lists the generalized modulus models developed using the combined test data and gives the model parameters obtained from stepwise multiple regression analyses. Table 3 presents permanent deformation models developed for the oil sand materials. Detailed test data and individual models developed for each oil sand material tested, i.e., SE-09, SE-14 and AU-14 samples, are presented elsewhere [9-14]. It should be mentioned that some of the models presented in this paper provide enhancements over the previous models [9-14].

A more practical model for oil sand materials should account for the additional effects of temperature and bitumen content in the oil sand. Recall that oil sand materials depend largely on the applied stress states, bitumen content and temperature [2]. Therefore, model 3 of bulk modulus and dynamic modulus models listed in Table 2 can be proposed as a more advanced model for field validation to estimate the bulk modulus and dynamic modulus behavior of these oil sands. Similarly, model 4 of the shear modulus models can be proposed for shear modulus characterization of oil sand materials.

The resilient modulus and permanent deformation models were rather selected after additional laboratory tests were conducted on newly prepared specimens of all the three oil sand materials to verify performances of various models suggested in Tables 2 and 3. Generally, close agreements between results from the original and the verification tests demonstrated good repeatability of the test data and likewise good performances of the individually developed models. For resilient behavior characterization, resilient modulus predictions were quite better than models 2 and 3. Therefore, it would be reasonable to propose model 1 for further calibration as the resilient modulus model for oil sands. Also, it was found that model 4 of the permanent strain models would predict the oil sand permanent deformation accumulation in the field better than models 1–3. These observations support the fact that bitumen content and temperature have major effects on the stiffness behavior of oil sand materials in the field [2].

TABLE 2— *Oil sand modulus characterization models.*

Bulk Modulus K Models						
Model 1:	$K = A\times\sigma^{k_1}$					
Model 2:	$K = A\times\sigma^{k_1}T^{k_2}$					
Model 3:	$K = A\times\sigma^{k_1}w_b^{k_2}T^{k_3}$					
Model Parameters	A	k_1	k_2	k_3	R^2	*RMSE*
Model 1:	0.6	0.441	-	-	*0.69*	*0.096*
Model 2:	2.6	0.441	-0.585	-	*0.82*	*0.075*
Model 3:	17.8	0.441	-0.585	-0.607	*0.93*	*0.049*

Shear Modulus G Models							
Model 1:	$G = A\times\theta^{k_1}$						
Model 2:	$G = A\times\theta^{k_1}\tau_{oct}^{k_2}$						
Model 3:	$G = A\times\theta^{k_1}\tau_{oct}^{k_2}w_b^{k_3}$						
Model 4:	$G = A\times\theta^{k_1}\tau_{oct}^{k_2}w_b^{k_3}T^{k_4}$						
Model Parameters	A	k_1	k_2	k_3	k_4	R^2	*RMSE*
Model 1:	0.32	0.866	-	-	-	*0.19*	*0.356*
Model 2:	0.10	2.019	-1.592	-	-	*0.72*	*0.211*
Model 3:	1.29	2.021	-1.596	-1.059	-	*0.80*	*0.181*
Model 4:	57.8	2.029	-1.614	-1.059	-1.183	*0.87*	*0.147*

Dynamic Modulus $\|E^*\|$ Models						
Model 1:	$\left\|E^*\right\| = A\times\theta^{k_1}$					
Model 2:	$\left\|E^*\right\| = A\times\theta^{k_1}w_b^{k_2}$					
Model 3:	$\left\|E^*\right\| = A\times\theta^{k_1}w_b^{k_2}T^{k_3}$					
Model Parameters	A	k_1	k_2	k_3	R^2	*RMSE*
Model 1:	0.004	1.698	-	-	*0.63*	*0.304*
Model 2:	0.431	1.710	-1.882	-	*0.78*	*0.235*
Model 3:	204.2	1.712	-1.882	-1.930	*0.90*	*0.160*

Resilient Modulus M_R Models							
Model 1:	$M_R = A\times\theta^{k_1}w_b^{k_2}T^{k_3}$						
Model 2:	$M_R = A\times\left(\frac{\theta}{P_a}\right)^{k_1}\left(\frac{\tau_{oct}}{P_a}\right)^{k_2} w_b^{k_3}T^{k_4}$						
Model 3:	$M_R = A\times\left(\frac{\theta}{P_a}\right)^{k_1}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_2} w_b^{k3}T^{k_4}$						
Model Parameters	A	k_1	k_2	k_3	k_4	R^2	*RMSE*
Model 1	33.1	0.690	-0.464	-0.533	-	*0.88*	*0.074*
Model 2	619.7	0.770	-0.162	-0.467	-0.528	*0.93*	*0.057*
Model 3	865.8	0.771	-0.478	-0.466	-0.530	*0.93*	*0.059*

TABLE 3— *Oil sand permanent strain models.*

Model 1:	$\varepsilon_p = A \times N^{k_1} \left(\sigma_1 / \sigma_3 \right)^{k_2}$
Model 2:	$\varepsilon_p = A \times N^{k_1} \left(\sigma_1 / \sigma_3 \right)^{k_2} \sigma_d^{k_3}$
Model 3:	$\varepsilon_p = A \times N^{k_1} \left(\sigma_1 / \sigma_3 \right)^{k_2} \sigma_d^{k_3} w_b^{k_4}$
Model 4:	$\varepsilon_p = A \times N^{k_1} \left(\sigma_1 / \sigma_3 \right)^{k_2} \sigma_d^{k_3} w_b^{k_4} T^{k_5}$

Model Parameters	*A*	k_1	k_2	k_3	k_4	k_5	R^2	*RMSE*
Model 1	0.013524	0.186	2.244	-	-	-	*0.85*	*0.196*
Model 2	0.002903	0.186	1.875	0.385	-	-	*0.90*	*0.188*
Model 3	0.011442	0.186	1.874	0.387	0.645	-	*0.92*	*0.185*
Model 4	0.001389	0.186	1.875	0.386	0.650	0.661	*0.93*	*0.185*

The generalized models selected and proposed for use in this study to characterize oil sand materials are presented in Eqs. 8–13. Note that the shear strength models (Eqs. 13*a* and 13*b*) were obtained directly from the Mohr-Coulomb relationship presented in Eq. 2.

Bulk modulus K model:

$$K = 17.8 \times \sigma^{0.441} w_b^{-0.585} T^{-0.607} \qquad R^2 = 0.93 \qquad RMSE = 0.049 \tag{8}$$

Shear modulus G model:

$$G = 57.8 \times \theta^{2.029} \tau^{-1.614} w_b^{-1.059} T^{-1.183} \qquad R^2 = 0.87 \qquad RMSE = 0.147 \tag{9}$$

Dynamic modulus |E*| model:

$$\left| E^* \right| = 204.2 \times \theta^{1.712} w_b^{-1.882} T^{-1.930} \qquad R^2 = 0.90 \qquad RMSE = 0.161 \tag{10}$$

Resilient modulus M_R model:

$$M_R = 33.1 \times \theta^{0.690} w_b^{-0.464} T^{-0.533} \qquad R^2 = 0.88 \qquad RMSE = 0.074 \tag{11}$$

Permanent strain ε_P model:

$$\varepsilon_p = 1.389\times10^{-3} N^{0.186} \left(\sigma_1 / \sigma_3 \right)^{1.875} \sigma_d^{0.386} w_b^{0.650} T^{0.661} \qquad R^2 = 0.93 \qquad RMSE = 0.185 \qquad (12)$$

Shear strength models at 20^{o}C:

$$\text{SE-09}: \tau_{max} = 0.82\sigma_n + 6.2 \qquad \text{SE-14}: \tau_{max} = 0.72\sigma_n + 15.2 \qquad \text{AU-14}: \tau_{max} = 0.63\sigma_n + 22.9 \qquad (13a)$$

Shear strength models at 30^{o}C:

$$\text{SE-09}: \tau_{max} = 0.65\sigma_n + 17.6 \qquad \text{SE-14}: \tau_{max} = 0.59\sigma_n + 29.5 \qquad \text{AU-14}: \tau_{max} = 0.55\sigma_n + 31.3 \qquad (13b)$$

The significantly high correlation coefficients (R^2) and low root mean square error (*RMSE*) values obtained from the SAS stepwise multiple regression analyses for all the models (Eqs. 8 – 12) implied that the individual models could be proposed for routine use in the estimation of oil sand field modulus and deformation characteristics. Further, the p-values for all selected models were less than 5% (i.e., p-value < 0.05), implying that there is high confidence in the correlation of the modulus and deformation (i.e., dependent variables) with the independent variables used to develop the models. However, further validation and verification of the models can be accomplished using results of additional laboratory and field tests.

As shown in Tables 2 and 3, the effect of stress state is significant on all the selected models for the oil sand materials. Specifically, Eqs. 8 – 12 show that bulk stress affects the modulus of the oil sands significantly. The moduli generally increase at bulk stress levels, indicating that oil sands become stress-dependent materials during loading. Previous research indicated similar trends for hot-mix asphalt materials at high temperatures [30, 31]. Note that the coefficients of Eqs. 8–11 are proportional to the moduli of the oil sand materials. This implies that these coefficients should always be positive since the modulus property cannot be negative. Also, increasing the bulk stress in these models should produce a stiffening of the oil sand materials to result in a higher modulus values. That is, the exponents of the bulk stress should also be positive in these equations. On the other hand, the exponents of bitumen content and temperature in the models should be negative since increasing these parameters would generally result in a softening of bituminous materials.

This suggests that at higher temperatures, the modulus or stiffness of the oil sand material would be mainly influenced by the sand skeleton, and increase as the mining trucks get heavier in the field. Thus, the moduli of oil sand materials would exhibit stress hardening behavior similar to the case of unbound granular materials. On the other hand, permanent deformation accumulation increases with increasing stress values, as well as increasing bitumen content and temperature. Similar trends were observed in the field [2]. Thus, the exponents of all the parameters in the permanent strain model should be positive. High stresses and temperatures as well as high bitumen contents would induce large permanent deformations in the oil sand materials especially at the initial load application.

Conclusions

This paper presented findings from a comprehensive laboratory research study conducted at the University of Illinois at Urbana-Champaign in the US on three oil sand materials with bitumen contents of 8.5 %, 13.3 % and 14.5 % by weight. Overall, five new and improved laboratory test procedures were presented for determining shear strength, bulk modulus, resilient modulus and permanent deformation characteristics, shear modulus, and dynamic modulus of the oil sand materials. The laboratory testing program conducted with these tests provided a large amount of data for the oil sand materials.

Two important conclusions can be drawn from the study on the oil sand materials:

- A suite of laboratory test procedures has been developed for oil sand materials. The test procedures provide a platform and opportunity that can be harnessed to establish standard ASTM laboratory test protocols for the sustainable use of oil sand deposits as temporary and permanent roads materials in mine fields.

- Material characterization and performance models have been developed to properly characterize field behavior of oil sand materials under both static and dynamic loading conditions. Although field calibration will be necessary to ascertain the overall performance of the models, the developed models were found to be reasonable for practical use based on their high correlation coefficients.

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