Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 3(6):286-294

Case Study: Dynamic Modulus Characterization of Naturally Occurring Bituminous Sands for Sustainable Pavement Applications

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Abstract: Oil sand is a generic name given to naturally occurring deposits of bituminous sand materials that are mined for crude oil production. These materials are currently used as subgrade materials of temporary and permanent roads in oil sand fields. The presence of high bitumen content makes oil sand materials problematic for field operations of off-road haul trucks and shovels during the warm spring and summer months. The behavior of oil sand materials is primarily dependent upon stress states, temperature, and the rate of loading or frequency. To effectively account for temperature and loading frequency, dynamic modulus is the preferred material property to characterize bituminous materials. In this paper, dynamic modulus is determined for three types of oil sand materials with natural bitumen contents of 8.5, 13.3, and 14.5% by weight using cyclic load triaxial test procedure. All the three oil sand samples were compacted close-to-field densities and then tested at two temperatures and three loading frequencies (related to field trafficking speeds) at different stress states. Based on the test results, dynamic modulus was modeled as a power function of the applied stress states and temperature. Using all the test data obtained from the three oil sand samples, unified dynamic modulus characterization models were successfully developed to account for stress state, bitumen content, and temperature. The proposed model can be calibrated for field practical use to estimate modulus and deformation behavior of these oil sand materials for their sustainable use in pavement applications.

Key words*: Bitumen content; Bituminous/oil sands; Cyclic load triaxial test; Dynamic modulus; Temperature.*

Introduction

Oil sands, sometimes called as tar sands, are natural deposits of bituminous sand materials that are rich in bitumen content to the extent that oil can be extracted from these deposits. Oil sands are found worldwide. The largest and most thoroughly studied deposits are located in Canada, United States, and Venezuela. The Alberta Province in Canada has the world's largest deposit of oil sands. Oil sand surface mining involves excavation to remove the overburden and providing access to the mineral sands below it using haul trucks and shovels. 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., inorganic materials of the oil sand composition normally constitutes about 80% by weight, with bitumen and water constituting about 15 and 5%, respectively [1]. Oil sand materials are currently used as construction materials of temporary and permanent roads in oil sand fields for operating large capacity haul trucks and shovels. These materials often exhibit stress dependent, viscoelastic, and plastic behavior under off-road 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, and the rate of loading or frequency [2].

Dynamic modulus is a stiffness parameter used mainly to characterize behavior of bituminous materials under varying temperature and loading frequencies [3]. The theory behind dynamic modulus is well documented through several studies [4-7]. In these studies, the values of dynamic modulus obtained from maximum stress and strain of cyclic loading tests are used as performance criteria for bituminous materials over a range of field loading frequencies and temperatures. Thus, dynamic modulus properties have been extensively studied to describe behavior of bituminous materials. However, no comprehensive laboratory test procedure or set of data is currently available to determine dynamic modulus properties of oil sand materials. Instead, experimental research studies on oil sands have primarily focused on using static loading conditions to obtain stress-strain data to characterize shear strength and elastic behavior [8-12]. To properly characterize modulus and deformation characteristics of oil sand materials under dynamic traffic loading, laboratory tests should closely simulate field densities and applied stress states under realistic temperature and time rate of loading conditions.

The objective of this paper is to present the dynamic modulus properties of three oil sand materials with natural bitumen contents of 8.5, 13.3, and 14.5% by weight determined in the laboratory using a newly developed cyclic loading test procedure [13]. The test procedure, based on realistic field loading conditions of the oil sand materials, aims to establish characterization of the dynamic modulus behavior of oil sands for their sustainable use in pavement applications. The experimental program carried out on three oil sand materials with varying bitumen contents focused on conducting cyclic load triaxial tests under simulated close-to-field densities and applied stresses at three different loading frequencies and two temperatures. Based on the laboratory test data, dynamic modulus

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Note: Submitted October 27, 2009; Revised March 16, 2010; Accepted March 24, 2010.

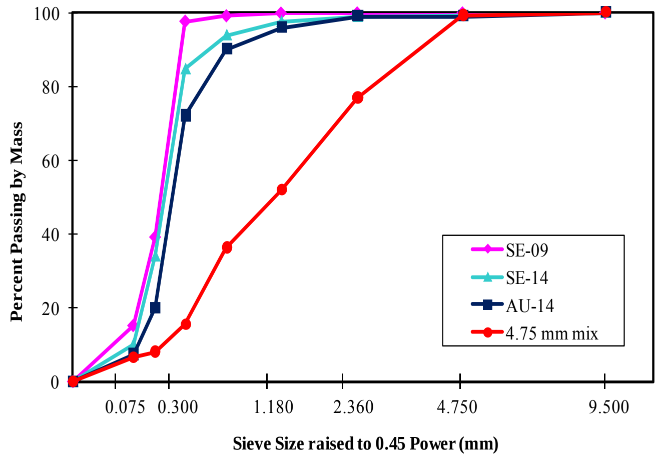

Fig. 1. Oil Sand Gradations Compared with 4.75*mm* NMAS Fine Asphalt Mixes.

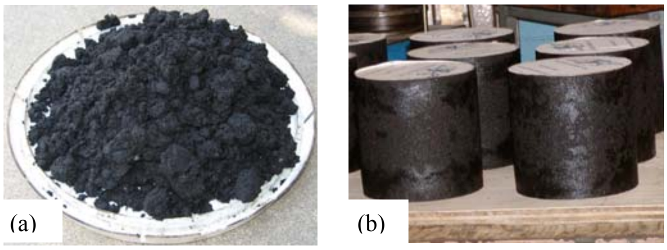

Fig. 2. Oil Sand Sample: (a) Loose State; and (b) Gyratory Compacted Specimens.

models are developed for each oil sand material using the applied stresses, and the loading conditions. Using all the test data for the three oil sands, combined dynamic modulus models are also developed to include applied stresses, bitumen content, and temperature as variables in the predictive equations established with the goal to characterize modulus and deformation behavior of the oil sand materials.

Materials Tested and Properties

Three types of oil sand materials selected for this study were obtained from Suncor Energy (SE), 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 ongoing research on these materials. Suncor Energy, Inc. provided two types, SE low and high grades with respect to the bitumen contents, whereas Syncrude Canada Ltd. provided one sample of the Aurora (AU) high grade oil sand. The soil and all 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 the laboratory tests.

The oil sand samples were initially tested for bitumen and water contents using American Association for State Highway and Transportation Officials (AASHTO) T 308 and T 265 test procedures, respectively [14, 15]. 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. Accordingly, the Suncor Energy high and low grades samples were designated as SE-09 and SE-14, respectively, and the Aurora high grade was designated as AU-14.

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 [16]. Gradation analyses performed on the oil sands show that SE-09 sample is finer with maximum particle size (D_{max}) of 0.60*mm* compared with 2.36*mm* for both SE-14 and AU 14 samples. Fig. 1 shows the gradations for the three oil sand mixtures. Note that these gradations were not designed but represent the actual particle size distributions of the naturally occurring oil sand mixtures. The gradations indicate that all the three oil sand samples are uniformly graded fine to medium sands, which are similar to grain size distributions for typical oil sand materials reported by Cameron and Lord [17]. Fig. 1 also compares oil sand particle size distributions with typical 4.75*mm* nominal maximum aggregate sizes (NMAS) of fine graded hot mix asphalt mixtures.

Sample Preparation

Field density levels and compaction properties of the oil sands were achieved in the laboratory samples using a gyratory compaction device. Cylindrical specimens of the oil sand materials, 150*mm* in diameter by 150*mm* high, were prepared for cyclic triaxial testing using an Australian Industrial Process Controls Ltd. (IPC) Servopac gyratory compactor. The specimens were compacted at different density levels depending on the applied number of gyrations at the approximate density states in the field. A 150-mm diameter filter paper was placed at the bottom of a gyratory compaction mold. The required amount of oil sand material to achieve the expected density was placed in the mold. Another filter paper was placed on top of the specimen and compaction was initiated until the expected specimen density was achieved by simultaneous action of static compression and shearing action resulting from the motion of specimen. When the compaction process was completed, the specimen was ejected from the mold by a pneumatic system setup.

The typical bulk densities achieved in gyratory compactors were 2,000kg/m^3 at 100 gyrations for SE-09 and 2,050kg/m^3 at 40 gyrations for SE-14. The density achieved for AU-14 was 2,050kg/m^3 at 25 gyrations. These achieved densities obtained for the 150*mm* in diameter by 150*mm* high cylindrical specimens prepared were very close to field density values reported by Joseph [2]. The air voids determined for the three oil sands after compaction using the AASHTO T 166 and AASHTO T 209 procedures were found to be 12.6, 8.0, and 6.7% for the SE-09, SE-14 and AU-14 samples, respectively [18, 19]. Following compaction, the oil sand specimens were placed in 0.6*mm* thick latex membrane and conditioned in a temperature chamber for a minimum of 6*hrs* before testing. Fig. 2 shows loose and compacted states of the AU-14 oil sand sample.

Experimental Program

Oil sand materials soften and become problematic at temperatures above 28°C in the field during warmer months to the extent that

Table 1. Experimental Program for the Oil Sand Study.

Loading Frequencies(*Hz*)	2		5		10	
	σ_3	σ_d	σ_3	σ_d	σ_3	σ_d
Stress States (*kPa*)	41.4	41.4	41.4	41.4	41.4	41.4
	69.0	41.4	69.0	41.4	69.0	41.4
	137.9	41.4	137.9	41.4	137.9	41.4
	206.9	41.4	206.9	41.4	206.9	41.4

Test Temperatures = 20 and 30°C
Total Number of Tests per Oil Sand Sample = 24 (72 Tests for SE-09, SE-14, and AU-14 Samples)

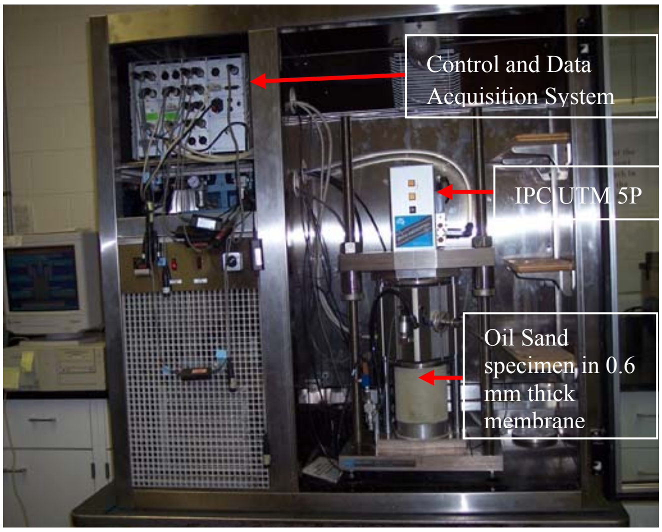

Fig. 3. University of Illinois RaTT Cell Showing Oil Sand Sample for Dynamic Modulus Testing.

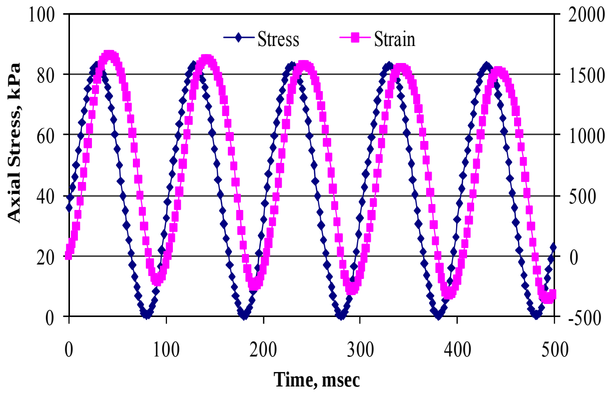

Fig. 4. Variations of Stress and Strain with Time for Typical Oil Sand Material Tested.

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 [20]. Joseph [2] noted from field studies that P&H 4100 BOSS shovels generated a static ground loading of up to 220*kPa*, and could induce a ground confinement of about 70*kPa*. The confinement under trucks could be up to approximately 300*kPa*.

Table 1 lists the test frequencies and stress states designed to investigate the dynamic modulus behavior of the three oil sand materials at different loading conditions and stress states. Testing was planned to obtain 250 data points for each test at each test temperature in the factorial. Replicate tests were run at several stress states where necessary.

Test Procedure and Laboratory Testing

The cyclic loading test procedure used for this study differed in the stress states applied to adequately determine dynamic modulus properties and characterize the stiffness behavior of the oil sand materials. This new procedure applies a complete sine load waveform at loading frequencies of 2, 5, and 10*Hz*, and two test temperatures of 20 and 30°C to simulate spring and summer field loading conditions of the oil sand materials [13]. At different constant confining pressures, cyclic/dynamic stress is applied on the specimen, and stresses and strains in vertical direction are recorded to compute dynamic modulus properties of the materials tested.

A laboratory test setup of commercially available advanced cyclic/repeated load triaxial testing device at ATREL, namely rapid triaxial testing cell (RaTT cell), was used for applying stresses on the specimen (see Fig. 3). The RaTT cell device uses IPC's universal testing machine series, UTM-5P system, with an environmental chamber, which is temperature controlled, to apply loading to test specimens. The ATREL RaTT cell setup has been extensively used to characterize the modulus behavior of bituminous and granular materials [21, 22]. 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, 69.0, 138.0, and 207.0*kPa*. The specimen's vertical deformation was determined by averaging readings of the two axial linear variable displacement transducers (LVDTs). Axial stresses and the corresponding axial strains were recorded for five load cycles for each test to compute the dynamic modulus of the oil sand materials. A total of 24 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, the cyclic stress was applied on each oil sand sample at the four different confining stress levels, two test temperatures of 20 and 30°C and three loading frequencies of 2, 5, and 10*Hz*.

Analyses and Discussion of Test Results

The test data used for the dynamic modulus analyses include the time of loading, stresses, and strains. Fig. 4 shows the typical variations of the applied axial stress and the corresponding measured axial strain with time. A cyclic pressure of 41.4*kPa* was applied over a 41.4-kPa confining pressure for 5 load cycles at a selected loading frequency of 10*Hz* for the AU-14 oil sand sample.

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* [3, 23, 24]. 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 by Eqs. (1a) and (1b), respectively.

$$\sigma^* = \sigma_0 e^{i\omega t} \tag{1a}$$

$$\varepsilon^* = \varepsilon_0 e^{i(\omega t - \delta)} \tag{1b}$$

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, $\delta = 0^o$, and for a pure viscous material, $\delta = 90^o$. Mathematically, the dynamic modulus is defined as the maximum (peak) dynamic stress divided by the recoverable maximum (peak) axial strain.

From Eqs. (1a) and (1b) the complex modulus, $E^*(i\omega)$, is defined as the complex quantity in Eq. (2).

$$E^*(i\omega) = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0} e^{i\delta} = E' + iE'' \tag{2}$$

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. (3).

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{3}$$

In this study, the generalized function presented in Eq. (4) was used to fit the test data to obtain the peak values for computing dynamic moduli of the oil sand materials. A least squared error regression analysis was performed to determine the amplitude of the sinusoidal pulse for the peak stresses and strains. The ratio of the peak axial stress to peak axial strain obtained from the regression analysis was used to calculate the dynamic modulus of the material tested (see Eq. (3)). Eq. (4) shows the mathematical curve fit function F(t) used to obtain the stress and strain amplitudes to calculate the dynamic modulus values of the oil sand samples.

$$F(t) = a_0 + a_1 t + b\cos(\omega t) + c\sin(\omega t) \tag{4a}$$

$$\text{Amplitude} = \sqrt{b^2 + c^2} \tag{4b}$$

where a_0, a_1, b, and c are regression constants.

A total of about 250 stress-strain data points was recorded for one test or one oil sand specimen at one test temperature. Thus, the laboratory testing program for one oil sand sample provided about 6,000 data points from 12 stress-strain conditions at the two test temperatures. The analyses included dynamic modulus computations and material characterization models were developed to describe the behavior of the oil sand materials. Tables 2 and 3 summarize the test results obtained for the SE-09, SE-14, and AU-14 oil sand samples subjected to the applied confining (σ_3) and cyclic/dynamic (σ_d) stresses at two test temperatures and three loading frequencies.

As expected, the dynamic moduli of all the oil sands tested were generally higher at 20°C than at 30°C. The AU-14 sample with bitumen content of 14.5% generally, had the lowest dynamic moduli and the SE-09 sample with bitumen content of 8.5% had the highest dynamic moduli at all the test conditions. On the average, dynamic moduli of SE-09 sample were about 1.6 and 2.6 times of the average dynamic moduli of the AU-14 sample at 20 and 30°C, respectively. Generally, the phase angles of AU-14 were the highest, and the SE-09 phase angles were the lowest as expected from these materials. No significant differences were found between dynamic moduli and phase angles of the AU-14 and SE-14 (with bitumen content $w_b = 13.3\%$) samples, which could be attributed to the similar amount of bitumen contents in the two samples. Under the same test conditions, the phase angles (δ) of all the oil sand materials are higher at 30°C than at 20°C. This is also observed in asphalt mixtures with higher phase angles obtained at higher temperatures than lower temperatures. Generally, at the same loading frequency, the phase angle values of the oil sands are much larger at lower confining stresses.

The variation in air voids content did not influence results of the oil sand materials as the SE-09 with air voids content of 12.6% would have the lowest stiffness properties and the AU-14 with air voids content of 6.7% the highest stiffness properties. Note that the three oil sand samples were tested at their naturally occurring state, i.e. no test could be conducted to check variation of air void contents with stiffness. It can only be assumed that the bitumen content of SE-09 is close to the optimum whereas the bitumen content of AU-14 and SE-14 samples are above the optimum state. Thus, the amount of bitumen content appears to have the dominant effect on the dynamic modulus properties of oil sand materials when compared to the effect of density. These laboratory findings also agree very well with the observed field behavior of oil sand materials [2].

Since no rheology test could be performed on the bitumen to compare results with the dynamic modulus test results, it is not clear if any reasonable correlations exist between the rheological properties and dynamic modulus at the two field temperatures. This is partly due to the fact that no information was found from the most recent field study conducted on these oil sand materials in relation to the rheological properties of the bitumen [2]. However, because the three oil sand samples were obtained from the same natural oil sand deposit, it can be reasonably assumed that the rheological properties should be similar.

The effects of several important factors, i.e., temperature, applied stress, and loading frequency, on the dynamic moduli of the three oil sand materials were investigated next. Note that the applied cyclic/dynamic stress (σ_d) was kept constant for all the tests conducted. Therefore, the different confining stresses applied capture the influence of stress state on dynamic modulus properties of the oil sand materials.

Figs. 5 to 7 show the measured dynamic moduli for the three oil sand samples as a function of loading frequency at 20 and 30°C. For the same loading frequency, the magnitude of the dynamic modulus in general decreases with an increase in temperature. Also, at the same test temperature, the magnitude of the dynamic modulus generally increases with an increase in the loading frequency although in some instances the increase appears not to be significant. For example, such an increase was rather high in the SE-14 and AU-14 materials at 30°C and high confining stress states. An average

Table 2. Dynamic Modulus Test Results for Oil Sand Samples at Temperature = 20°C.

Frequency (*Hz*)	SE-09 Sample				SE-14 Sample				AU-14 Sample			
	σ_3 (*kPa*)	σ_d (*kPa*)	$\|E^*\|$ (*MPa*)	δ (Deg.)	σ_3 (*kPa*)	σ_d (*kPa*)	$\|E^*\|$ (*MPa*)	δ (Deg.)	σ_3 (*kPa*)	σ_d (*kPa*)	$\|E^*\|$ (*MPa*)	δ (Deg.)
2	41.1	41.2	54.1	30.3	41.2	41.0	15.9	39.4	44.0	41.8	12.9	40.4
5	41.1	40.9	87.8	29.3	41.2	40.6	27.2	40.9	43.9	42.3	25.1	42.1
10	41.0	40.7	110.4	29.9	41.1	41.0	43.5	42.7	43.5	42.5	45.0	41.7
2	69.0	41.4	171.2	14.9	69.0	41.3	52.2	31.0	70.7	42.9	30.6	35.9
5	69.0	41.2	189.7	17.8	69.0	40.9	66.6	33.0	70.8	40.6	56.0	38.3
10	69.0	41.0	205.1	21.0	69.0	42.0	100.1	32.2	70.9	41.1	103.7	32.6
2	139.0	41.4	287.1	12.0	139.0	42.2	177.3	15.6	140.3	41.1	174.8	16.3
5	139.0	40.8	308.1	14.7	139.0	41.6	192.7	18.9	140.3	41.0	202.7	17.0
10	139.0	39.2	327.5	15.0	139.0	41.3	236.8	20.5	140.4	40.8	230.1	16.0
2	208.9	40.2	373.3	10.5	208.9	42.2	285.0	12.6	209.9	40.6	287.8	11.0
5	208.9	39.5	411.5	12.5	208.9	41.1	313.8	14.4	209.9	40.3	305.7	12.5
10	208.9	40.4	502.5	14.7	208.9	39.3	343.2	18.4	210.0	38.9	334.3	12.0

Table 3. Dynamic Modulus Test Results for Oil Sand Samples at Temperature = 30°C

Frequency (*Hz*)	SE-09 Sample				SE-14 Sample				AU-14 Sample			
	σ_3 (*kPa*)	σ_d (*kPa*)	$\|E^*\|$ (*MPa*)	δ (Deg.)	σ_3 (*kPa*)	σ_d (*kPa*)	$\|E^*\|$ (*MPa*)	δ (Deg.)	σ_3 (*kPa*)	σ_d (*kPa*)	$\|E^*\|$ (*MPa*)	δ (Deg.)
2	41.2	40.8	19.8	36.2	43.4	41.8	9.0	42.4	43.4	41.8	8.84	42.0
5	41.2	40.4	28.6	35.8	42.0	40.0	12.1	42.8	43.9	41.3	11.7	44.2
10	41.3	39.8	34.2	36.4	42.2	40.0	17.8	45.3	43.7	41.3	17.6	43.2
2	69.0	41.3	77.3	22.1	70.9	41.2	14.1	33.7	70.8	41.3	15.3	32.6
5	69.0	41.0	103.5	29.8	69.7	40.3	21.3	34.7	71.1	41.1	20.9	39.0
10	69.0	40.9	112.4	29.9	69.7	42.0	33.0	35.8	71.2	40.9	32.9	38.5
2	139.0	41.3	224.5	20.0	140.0	43.4	39.9	23.5	140.3	41.2	48.3	25.4
5	138.9	40.7	235.2	20.8	138.9	42.9	60.1	24.4	140.2	40.9	71.0	29.4
10	138.9	39.1	246.4	20.7	139.0	41.8	111.6	29.7	140.4	40.1	110.0	30.1
2	208.9	40.1	311.4	17.0	209.7	42.8	100.1	18.3	209.9	40.5	108.4	16.1
5	209.6	38.5	340.0	16.3	208.9	40.7	152.8	18.3	209.9	39.2	154.5	17.7
10	208.9	39.4	414.2	16.7	208.9	41.2	240.8	18.8	209.9	36.6	233.2	17.3

increase of about 40% in dynamic modulus was observed in the SE-09 sample when the loading frequency increased from 2 to 10Hz. Under the same conditions, there was more than 70% average increase in the dynamic modulus values for the SE-14 sample, and more than 100% for AU-14 sample at the two test temperatures. This implies high grade oil sand materials are very sensitive to changes in temperature and loading frequency.

Clyne et al. [25] reported a similar effect of loading frequency on the stiffness of bituminous materials. Generally, the dynamic modulus of the three oil sand materials significantly increased with increasing confining stress at the same loading frequencies and temperatures. Agar et al. [8] and Dusseault and Morgenstern [9] reported that oil sand materials exhibited dense interlocking grain structure. At intermediate and high temperatures, the modulus property of most bituminous materials, e.g., hot-mix asphalt depends to a large extent on the aggregate interlock, which makes the material stiffer when confining stress increases. As shown in Figs. 5 to 7, the effect of the confining (or bulk) stress is significant. The modulus generally increases at higher confining stress levels. The increase in dynamic modulus is generally larger at 30°C than at 20°C due to the fact that oil sands become more stress-dependent at higher temperatures. Uzan [26] and Pellinen [27] found similar behavior for hot-mix asphalt materials, i.e., the increase in dynamic modulus was larger at high temperatures than at low temperatures.

Future studies on oil sand materials to include moisture damage, rheology, and mixing with regular mixtures shall support the use of oil sand materials as potential wearing courses to seek for optimum oil sand content instead of using them only as subgrades in flexible pavements.

Statistical Analyses and Model Development

Approximately 6,000 data points generated for each oil sand sample at the two test temperatures statistically provide a high confidence in the characterization models developed. The test results in this study show that oil sand behavior is mainly influenced by temperature and loading conditions, i.e., loading frequency and applied stresses, in accordance with the sample's bitumen content. In addition, to properly model the dynamic modulus of the oil sand there is also a need to include all the important field controlling factors in the material characterization. Field studies indicated that during the hottest months in spring and summer, oil sands soften to

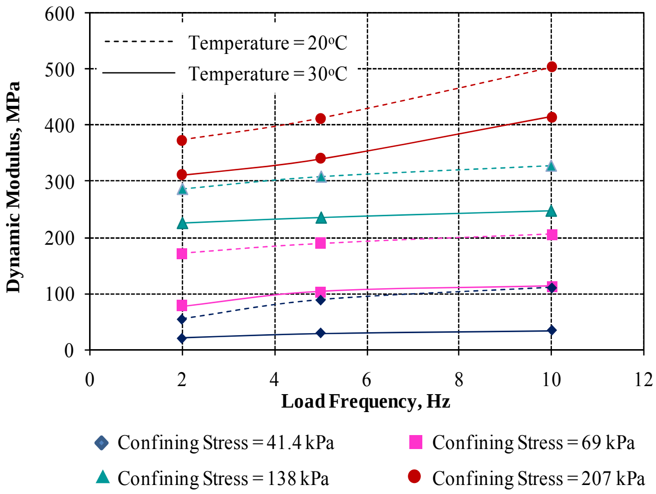

Fig. 5. Temperature, Stress, and Frequency Effects on Dynamic Modulus of SE-09.

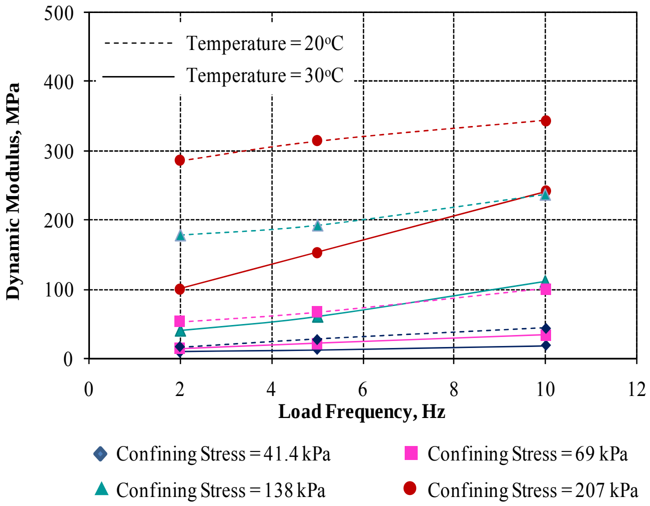

Fig. 6. Temperature, Stress, and Frequency Effects on Dynamic Modulus of SE-14.

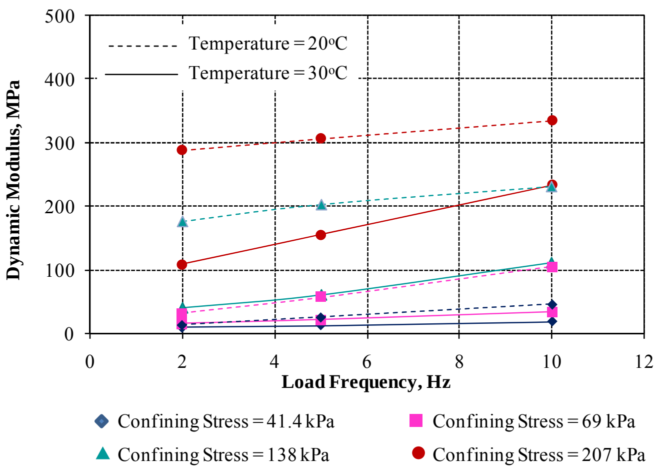

Fig. 7. Temperature, Stress, and Frequency Effects on Dynamic Modulus of AU-14.

the extent that routine operations of equipment such as trucks and shovels become problematic [2, 20]. This behavior is widely attributed to the presence of highly viscous bitumen in the oil sand, and the time dependent behavior of the material. Therefore, characterization models for oil sand materials should consider the effects of frequency, temperature, the applied loading response, and bitumen content.

The correlation coefficient (R-square) selection method in the SAS statistical software was first used to determine which independent variables were potential candidates for the models. The variables used in the selection include the applied stress states and measured strains, compacted air voids levels (densities), temperature, loading frequency, water content, and bitumen content. It was found that dynamic modulus of the oil sand materials tested have little correlation with water content, air voids level, loading frequency, and the measured strains. Therefore, the applied bulk stress (θ), temperature (T) and bitumen content (w_b) were used for modeling the dynamic modulus. Note that bulk stress ($\theta = \sigma_d + 3\sigma_3$) was used in the analyses instead of confining stress to include the applied cyclic/dynamic stress. Recall that increasing loading frequency directly affected dynamic moduli of the oil sand materials. However, for viscoelastic materials, the influence of increasing loading frequency is generally similar to the effect of decreasing temperature. This suggests that having a temperature in the model may provide a better indication than including loading frequency in the model. Joseph [20] indicated that the considerable amount of bitumen, high applied loads from mining equipment, and seasonal changes in temperature are major factors that control the modulus and deformation behaviour of oil sand materials in the field. Therefore, a practical oil sand model should account for the effects of the stress states, temperature, and bitumen content. Among all the mathematical forms considered, such as linear, nonlinear, logarithmic, and hyperbolic, the power function was the most suitable for modeling dynamic moduli of the oil sand materials.

Since the overall objective was to establish a basic understanding as well as to develop practical predictive equations to estimate field stiffness behavior of oil sands, the stress-strain data sets were combined to create individual databases of the three oil sand materials. The SAS software package was used to perform nonlinear multiple regression analyses to establish dynamic modulus characterization models for the oil sand materials. Table 4(a) lists two dynamic modulus models developed for each oil sand material and the model parameters obtained from the regression analyses. No significant differences were found among the model parameters for the three oil sands.

A close examination of the test results at the different test conditions, and the physical properties of the three oil sands such as particle size distribution, density, and water content with the assumption of similar bitumen properties suggested that the individual databases could be combined for further analyses. Therefore, it was reasonable to combine the test data to develop a generalized model for the oil sands. The combined database allowed bitumen content to be included as a variable in the analyses again with the assumption that bitumen rheological properties were similar among the three oil sands. Table 4(b) lists the generalized dynamic modulus models developed using the combined test data and gives the model parameters obtained from stepwise multiple regression analyses. The coefficient of correlation (R^2) value obtained for model 1 indicates stress dependency was significant and had to

Table 4(a). Regression Models Developed for Dynamic Modulus of Each Oil Sand.

Model 1	$\lvert E^* \rvert = A\,\theta^{k_1}$				
Model 2	$\lvert E^* \rvert = A\ \theta^{k_1} T^{k_2}$				
Model Parameters	Log A	k_1	k_2	R^2	RMSE
SE-09 Sample (Suncor Energy; Bitumen Content = 8.5%)					
Model 1	-1.469	1.455	-	0.79	0.186
Model 2	0.434	1.455	-1.369	0.88	0.140
SE-14 Sample (Suncor Energy; Bitumen Content = 13.3%)					
Model 1	-2.668	1.773	-	0.73	0.266
Model 2	0.614	1.782	-2.378	0.91	0.155
AU-14 Sample (Syncrude Canada; Bitumen Content = 14.5%)					
Model 1	-3.044	1.912	-	0.77	0.246
Model 2	-0.201	1.911	-2.044	0.90	0.163

Table 4(b). Generalized Models Developed for Dynamic Moduli of Oil Sand Materials.

Model 1	$\lvert E^* \rvert = A\,\theta^{k_1}$					
Model 2	$\lvert E^* \rvert = A\ \theta^{k_1} w_b^{k_2}$					
Model 3	$\lvert E^* \rvert = A\,\theta^{k_1} w_b^{k_2} T^{k_3}$					
Model	Model Parameters					
	Log A	k_1	k_2	k_3	R^2	RMSE
1	-2.352	1.698	-	-	0.63	0.304
2	-0.366	1.710	-1.882	-	0.78	0.235
3	2.310	1.712	-1.882	-1.930	0.90	0.160

be adequately considered for predicting dynamic moduli.

Since a comprehensive but yet practical model should also account for the additional effects of temperature and bitumen content in the oil sand, model 3 listed in Table 4(b) can be proposed as a more advanced model for field validation to estimate dynamic modulus behavior of these oil sands. The differences in R^2 values of the generalized models indicate that the bitumen content and temperature have significant effects on the dynamic modulus. For instance, the R^2 value was improved by more than 20% when the bitumen content term was included in model 2, and about 42% after both bitumen content and temperature terms were included in the model 3. This observation supports the fact that bitumen content and temperature have major effects on the stiffness behavior of oil sand materials in the field [2]. The high R^2 value obtained for model 3 ($R^2 = 0.9$) indicate that the model can be proposed for routine use in the estimation of oil sand field moduli. Further validation and verification of model 3 can be accomplished using results of additional laboratory and field tests.

The selected dynamic modulus model of the oil sand materials is given as follows:

$$\lvert E^* \rvert (MPa) = 204\,\theta^{1.712}\, w_b^{-1.882}\, T^{-1.930} \qquad (5)$$
$$R^2 = 0.90,\ RMSE = 0.161$$

In this equation, the coefficient representing model parameter A in Table 4(b) is proportional to the dynamic moduli of the oil sand materials. This implies that the values of A should be positive since modulus cannot be negative. Also, increasing the bulk stress in the model should produce a stiffening of the oil sand materials to result in a higher dynamic modulus. That is, parameter k_1 of the bulk modulus term should be positive. On the other hand, parameters k_2 and k_3 in the model should be negative since increasing bitumen content and temperature generally results in a softening of bituminous materials. This suggests that at higher temperatures the dynamic 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 modulus or stiffness of oil sand materials would exhibit stress hardening behavior similar to the case of granular materials.

Summary and Conclusions

Oil sand materials exhibit stress dependent, viscoelastic and plastic behavior under dynamic loading of off-road construction and mining equipment. Oil sands are currently used as construction materials, specifically as subgrade materials for temporary and permanent roads in oil sand fields for hauling activities. The applied load levels, i.e., stress states, temperature, and loading frequency mainly affect behavior of oil sand materials in the field. Several studies have indicated that dynamic modulus better characterizes the stiffness behavior of bituminous materials compared to the resilient modulus, which is often used for subgrade soils and unbound aggregate base/subbase materials. However, no studies in the literature were found to compare dynamic modulus of oil sands at different temperatures and loading frequencies as well as different loading stress states.

This paper dealt with measuring and characterizing dynamic modulus properties of three types of oil sands referred to as SE-09, SE-14, and AU-14, with bitumen contents of 8.5, 13.3, and 14.5% by weight, respectively. A newly proposed cyclic load triaxial test procedure applied stress states determined from typical field loading characteristics of haul trucks and mining equipment. The experimental program carried out on the three oil sands involved conducting dynamic modulus tests under simulated close-to-field densities and applied stress at three different loading frequencies and two temperatures. Bitumen content commonly affected dynamic modulus of the oil sand materials with the sample with lowest bitumen content having the highest modulus values compared to lower modulus values for the oil sand sample with higher bitumen content. Generally, the dynamic modulus behavior of all the three oil sand materials under different temperatures and loading frequencies were typical of bituminous materials.

Based on the database established from the testing program, oil sand dynamic modulus models were developed as power functions of the applied bulk stresses and temperature for each oil sand material. When the entire test data from the three oil sands were combined, unified/generalized dynamic modulus models were successfully developed to account for the test variables, i.e., applied bulk stress, temperature, and bitumen content. A more accurate approach would be to use dynamic modulus models for each oil sand material with known bitumen property separately. The models obtained from the dynamic modulus tests for the oil sand materials were found to be reasonable based on high correlation coefficients, although field calibration factors will be necessary to ascertain the overall performance of the models. The proposed dynamic modulus model provides practical predictive equations that may be calibrated or validated, and used in the field to estimate stiffness and deformation behavior of oil sand materials at different stress states and temperatures. Further validation and verification plan is recommended to test the validity of the proposed model with results of additional laboratory and field tests of oil sand materials having similar characteristics as those used in this study.

Acknowledgements

The authors would like to acknowledge Dr. Liqun Chi of Caterpillar, Inc. of Peoria, Illinois for providing the oil sand samples and for his valuable insights in this Caterpillar funded study. Also, the contributions of Dr Kaiming Xia, formerly of Caterpillar, Inc., to this study are greatly appreciated.

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